

1980

Effect of internal and external damage on deterioration rate of shelled corn

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RATE OF SHELLLED CORN

Iowa State University

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Effect of internal and external damage on deterioration
rate of shelled corn

by

Ahmad Kalbasi-Ashtari

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
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1980

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DEDICATION

*To the memory of my father,
Esmáíl,
the Islamic figure,
who died for his faith in Islam
and who loved agriculture
and food production.*

INTRODUCTION

Rapid mechanization and modernization of grain farming have aggravated some problems of quality control during harvesting, handling, storing, drying and transportation processes of shelled corn. About 79 percent of Iowa's 12.5 million acres of corn was harvested with a conventional combine in 1978 (Crop and Livestock Reporting Service, 1979). This is an increase of 2 percent from 1977. Mahmoud and Buchele (1975) indicated that mechanical damage to corn kernels is a problem arising from field shelling and Buchele (1977) suggested every additional operation, such as drying, storing and transportation, causes further damage to kernels and reduces the physical quality of the corn.

Since the major portion of corn damage occurs while the ears and shelled kernels pass through the shelling crescent of the combine harvester, several approaches have been taken to minimize this damage portion. Approaches have included rubber shellers, axial-flow combines, design improvement of conventional combines, and damage-resistant corn varieties. Industry representatives and researchers (Byg et al. 1966, Cooper 1968, Hall and Johnson 1970) have attempted to improve shelling performance by establishing optimum operating parameters, yet shelling damage during combine harvesting continues at objectionable levels.

Spoilage in shelled corn is related to moisture content, temperature and damage in corn kernels. Saul (1960) worked on artificially damaged corn and concluded that mechanical damage sustained by shelled corn during harvest has a marked effect on the rate of respiration and that respiration has a major effect on chemical components of corn.

Drying systems are used to preserve the good quality of corn and speed up the harvesting and handling processes. Furthermore, plant breeders have developed long season varieties of corn which yield considerably more than short season varieties, but usually dry only to about 26 to 28% rather than 18% moisture content for short season varieties and require forced, warm air drying (Buchele and Buchele 1977). Wet grain is dried either by natural air drying or heated air drying and the latter one can be low temperature or high temperature drying. Documented literature and recently Kalbasi-Ashtari et al. (1978); indicated that corn dried at low temperature has a noticeably higher quality than corn dried at high temperature. It has a very low percentage of crack formation, significantly lower mold count, and higher germination percentage than high temperature dried corn. As Shove and White (1977) indicated, stress cracks increase susceptibility to breakage, and corn dried at lower temperature has a greater potential of remaining unbroken during subsequent handling.

The allowable drying time is not unlimited in this system because of biological activity in the bin which results in grain spoilage. Therefore, it is necessary to evaluate the effect of mechanical damage occurring in a conventional combine on grain performance (grain quality) at the wet zone of in-storage drying.

Effects of internal cracks or invisible cracks which are a part of total mechanical damage in shelled corn are difficult to study and there are not many references in the literature on this subject. Steele (1967), showed that the undamaged portion of field-shelled corn has a rate of deterioration about 2 to 3 times faster than that of hand-shelled corn. They did not indicate a reason for this. It is our goal to analyze effects on corn storability of internal cracks in shelled corn.

OBJECTIVES

A study was undertaken to determine effects on deterioration rate of corn due to mechanical damage occurring during combine harvest.

The following were the objectives of this study:

1. To establish a relationship between the level of combine harvest damage to shelled corn and CO_2 production, O_2 uptake, and water uptake by kernels.
2. To evaluate the effect of screening out fines on the rate of CO_2 production.
3. To determine if there is a significant difference in deterioration rate between machine-shelled corn with no visible damage and hand shelled corn.

LITERATURE REVIEW

Nature and Causes of
Grain Damage

Except for the possible effects of insects and fungi on the crops, the mature grain in the field is undamaged and is an excellent food for man or animal. Most of the damage to the corn begins with the mechanical process of harvesting. In the conventional combine, the corn kernel is subjected to mechanical damage while passing through the shelling crescent (between steel cylinder and the steel concave). Mahmoud (1972) reported that the longer the kernel stayed in shelling crescent, the more damage it suffered. The increase in damage along the concave is caused by repetitive impacts from the rasp bars of the cylinder as ears and shelled kernels travel down the shelling crescent. Chowdhury and Buchele (1975) explained that those kernels shelled by direct impact are usually severely damaged, but those shelled by indirect impact are slightly damaged. Mechanical damage caused by the combine is partly invisible. This invisible damage might be external or internal. One of the purposes of this study is to show the effects of invisible injury to combine shelled corn. Chowdhury and Kline (1977) did some germination tests on whole undamaged seed corn and concluded that the high and low impacts and compressive loading between the rasp bar and the filler plates of the cylinder and steel

bars of the concave not only cause external damage to the sound pericarp of the seed, but cause internal injury like fissures and stress cracks inside the corn kernels as well. They indicated that kernels having internal injuries have a lower viability than whole sound kernels without any invisible cracks.

In the process of field harvesting, moisture content of the corn kernels has considerable effect on the amount and severity of the mechanical damage. Work by Miles (1956) indicated the advantage of shelling corn at lower moisture contents. Johnson and his associates (1963) observed a 3% reduction in dry kernel weights of corn shelled at 35% moisture as compared to corn shelled at 20% moisture. These workers indicated some of the losses resulting from high moisture corn shelling could be attributed to imperfect shelling in which a portion of a kernel tip was broken from the kernel and remained in the cob. Crockage which is a form of damage is the result of imperfect shelling and is related to the moisture content. Johnson et al. (1963) found 0.5% crockage after shelling corn at 20% moisture content, while at 35% moisture a crockage of 3.5% occurred. Many other research workers such as Lamp (1960), Burrough and Harbage (1953) and Morrison (1955) indicated increasing visual crockage (broken kernels and chips) with increasing moisture content. Barkstrom (1955), reported a trend of

increased crackage with decreased moisture content below about 20%. Chowdhury (1978) studied the effects of moisture content on the level of five different categories of damage (pericarp, crown, severe, embryo and sieved damage) and concluded that total damage is affected by moisture content of corn kernels. As the moisture content of the corn increases from 14 to around 20 percent, the amount of total mechanical damage caused by the combine is decreased. Around 22 percent moisture content, the overall damage level would be minimum. In other words with the increase of moisture content from 22 to even 35% moisture content, the total damage percentage increases. Waelti and Buchele (1969) indicated that kernel damage level was positively related to kernel moisture by the relationship $y = ax + b$, where $y = \log_{10}$ damage and $x = \log_{10}$ moisture content for the moisture range of 15 to 38%. Finally, Buchele and Buchele in 1977 suggested harvesting corn as close as possible to 22% moisture content with a grain combine and 18% moisture content with a picker sheller.

Besides the moisture content of corn, characteristics and adjustments of the combine have noticeable effects on the amount of damage in corn shelling by conventional combine. Mahmoud (1972) found that the separation percent of shelled kernels per unit length of concave was higher towards the front of the concave and lower towards the ends;

but the magnitude of the percentage mechanical damage was lower towards the front of the concave and increased linearly with an increase of concave length. Chowdhury (1978) indicated that total damage of corn kernels (a combination of different categories of kernel damage) increases with cylinder speed, and increased in the concave zone (distance from front of the concave) to some extent. Buchele (1977) mentioned that combine clearance at front and back of the concave has an effect on the magnitude of mechanical damage.

Some other factors such as freezing temperature and high temperature drying have some effects on rupture strength and stress crack formation on corn kernels, respectively. Sometimes because of immaturity and weather conditions the corn has to be harvested very late and corn is subjected to the varying temperatures ranging from subfreezing to a relatively high temperature. According to Srivastava et al. (1974), these changes, often diurnal, may subject the kernels to thermally-induced mechanical stresses and strains and it is possible that stresses and strains could affect the mechanical strength of corn kernels and their susceptibility to damage during subsequent handling operations.

Peplinski et al. (1975) show that high temperature drying at 80°C to 150°C lowered test weight and grade quality by 1 to 5 grade levels of USDA and increased the amount of damaged kernels. Ingeltt (1970), and Kline (1973) indicated

that corn dried at higher than 60°C exhibits stress cracking and is about 2 to 3 times more susceptible to breakage than corn dried with unheated air. Thompson and Foster (1963) found that high temperature drying may scorch or discolor the corn kernels and has a very important effect on grain grade. The third noticeable effect of high temperature drying is susceptibility of corn dried at high temperature to mold infestation. Tuite and Foster (1963) indicated that excessively heated corn becomes moldy at lower moisture levels than sound corn. Some other factors such as diameter of auger, speed of augers, speed of discharge in elevator and the height of discharge elevators in handling equipment have considerable effect on the amount of grain damage.

In general, grain damage can be classified into two categories: external and internal. Both types of damage may result in physical or physiological change of grain in the field and during harvesting, drying, storage and handling. External damage is caused mostly by combines (DeLong and Schwantes 1942, Bunnelle et al. 1954, Kolganov 1958; Arnold 1959, 1964, 1967, Waelti 1967, Cooper 1968 1971, Young 1968, Arnold and Roberts 1969; Hall and Johnson 1970, Ayres et al. 1972, Mahmoud 1972) and handling equipment (Sands and Hall 1969; Converse et al., 1970; Fiscus et al. 1971, and Keller et al. 1971). While internal damage (physical) is caused by climatic or environmental

change of the air surrounding the grain (Milner and Shellenberger 1953, Chung and Converse 1968), or by shelling and drying and other postharvest operations (Brekke 1965, 1966, 1968, Foster 1968, Chowdhury and Kline 1976, Hamdy et al. 1977, Shove and White 1977).

Attempts such as redesigning the conventional combine, designing completely new machines for shelling corn, using varieties of corn resistant to mechanical stress and strain have been done to minimize the level of mechanical damage. Al-Jalil et al. (1978) designed, constructed and tested a low damage corn shelling machine. The sheller consists of three inclined rollers rotating at different speeds. Although this new machine was able to shell the ear corn with an insignificant level of kernel damage, its shelling capacity was low in comparison with the capacity of the conventional shelling machines. Continuation of this research with his method to achieve a capacity comparable with conventional combines can present a new machine for shelling corn with a minimum level of mechanical damage.

United States Department of Agriculture Official
Grain Grading System

The USDA system consists of numerical grades, which are U.S. Number 1 through U.S. Number 5, and Sample Grade; which is for grain inferior to the lowest quality numerical grade. Table 1 shows the numerical grade requirements for

Table 1. Numerical grades and sample grade and grade requirements for corn (USDA, 1970). Includes the classes yellow corn, white corn, and mixed corn

	Minimum test weight per bushel lb.	Maximum limits			
		Moisture %	Broken corn and foreign material %	Total %	Heat-damaged kernels %
U.S. No. 1	56	14.0	2.0	3.0	0.1
U.S. No. 2	54	15.5	3.0	5.0	0.2
U.S. No. 3	52	17.5	4.0	7.0	0.5
U.S. No. 4	49	20.0	5.0	10.0	1.0
U.S. No. 5	46	23.0	7.0	15.0	3.0
U.S. sample grade ^a					

^aU.S. sample grade shall be corn which does not meet the requirements for any of the grades from No. 1 to No. 5, inclusive; or which contains stones; or which is musty, or sour, or heating; or which has any commercially objectionable foreign odor; or which is otherwise of distinctly low quality.

corn. According to this system, broken corn and foreign material shall be kernels and pieces of kernels of corn and all matter other than corn which will pass readily through a 4.76-mm round-hole sieve, and all matter other than corn which remains in the sieved sample.

The contemporary grading system of USDA does not account for all types of mechanical damage. According to Ayres et al. (1972) mechanical damage of combined corn ranges between 16.4 and 79.4% in a typical field shelling harvesting system, but only 0.1 to 3.8% was the cracked corn and foreign material that passed through a 4.76-mm, round-hole sieve. This indicates that only a fraction of the total mechanically damaged kernels is being accounted for by the present USDA grading system. This is one of the reasons that numerical grades do not accurately predict the storability of corn.

Techniques for Evaluation of Corn Damage

Besides the grading system used by USDA (USDA 1970, 1972), different methods are being used by the research workers for measuring the level of mechanical damage (both external and internal) and evaluation of grain quality. They are listed in brief form as follows:

1. Cold germination tests (Welch and Delouche 1969, Clark et al. 1969).

2. Seedling growth rate tests (Koehler 1957, Burris et al. 1969, Chowdhury and Kline 1976).
3. Standard germination test (Kolganov 1958, Chowdhury and Buchele 1976a).
4. Numerical damage index (Chowdhury and Buchele 1976a).
5. Acid germination test promoted by National Institute of Agricultural Engineers, Silsoe, England (Caldwell and Hampson 1958, Arnold 1964).
6. Topographical tetrazolium tests (Lakon 1949, Moore 1961, 1967, Chowdhury 1973).
7. Chemical test (Waelti 1967).
8. Turbidity analysis (Agness 1968).
9. Fat acidity test (Zeleny 1949, Baker et al. 1957, 1959).
10. Corn breakage tester (Agness 1968, Chung and Converse 1968, McGinty 1970, McGinty and Kline 1972, Herum 1977).
11. Rheological methods (Bilanski 1966, Mahmoud 1972).
12. Candling method (Desikachar and Subrahmanyan 1961, Thompson and Foster 1963, Kunze and Hall 1965, Brekke 1968, Stermer 1968, Ross and White 1971, Hamilton et al. 1972, Kunze and Prasad 1976).
13. Photo-elastic and numerical technique (Arnold and Roberts 1969).
14. Infrared photographic technique (Chung and Park 1971a).
15. Electric color sorting technique (Boyd et al. 1968, Sarkar and O'Brien 1975).
16. Electrostatic separation (Harmond et al. 1961).
17. Electronic method (Holaday 1964).

18. Photoelectric system (Norris 1955, Christenbury and Buchele 1977).
19. X-ray technique (Milner and Shellenberger 1953, Chung and Converse 1968, Welch and Delouche 1969, Cardwell and Crawford 1971).
20. Laser beam reflectance (Yoon 1969).
21. Colorimeter reflectance method (Wirtz 1971).
22. Light reflectance method (Johnson 1960, 1965, Anon. 1972, Parkins 1975).
23. Light transmittance technique (Birth 1957, 1960, Norris 1958, Johnson 1960, Rosenthal 1973, Massie and Norris 1975).

All of these techniques mentioned above have some advantages and disadvantages. Many of them are either not sensitive enough to show differences in damage levels or still under research and experiment. Some are relatively accurate but too expensive; some are cheap but not accurate enough.

As defined by the American Society of Agricultural Engineers Standard: ASAE S343 (Section 3), grain damage refers only to that attributable to the machine (Agricultural Engineers Yearbook, 1977). According to their definition, it shall be expressed as the percentage by weight, to the nearest one-tenth of damaged kernels in the sample. According to this standard the grain damage was divided into two categories: visible grain damage and invisible grain damage. The visible damage consists of kernels damaged where the seed coat appears broken to the naked eye. The invisible grain damage consists

of kernel damage which requires instrumentation or special procedures for determinations. Many research workers such as Mahmoud and Kline (1972), Ayres et al. (1972) and Chowdhury and Buchele (1976b), defined mechanical damage as fines and any kernel, broken, chipped, scuffed or having minute cracks in the pericarp.

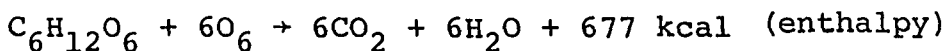
Biological Properties of Damaged Grain

It is very important to understand the effect of mechanical damage on grain performance during storage, i.e. the relation between mechanical injury due to the harvest process and physio-chemical properties of the corn during storage. Corn damaged during field shelling is more susceptible to invasion by insects, molds and fungi. These agents reduce its quantity, quality and storability (Saul 1967, Saul and Steele 1966). Mechanical damage affects short- and long-term storage. Saul and Steele (1966) reported that high moisture field shelled corn could not be stored more than a few hours without deterioration in quality. They said faster drying rates were required for damaged corn to prevent spoilage between harvesting and drying. Thus, mechanical damage also adds to the cost of drying. As Steele (1967) showed, the increased rate of deterioration (dry matter loss) caused by mechanical damage was estimated

by measurement of corresponding increases in CO₂ production of the grain. This is a reason the effect of damage level on grain storage in our studies was quantified by measuring the total CO₂ produced by respiration of the kernels.

Chemical Nature of Respiration

Since measuring CO₂ and the evaluation of conformity between O₂ uptake and CO₂ production of shelled corn under storage conditions is one of the objectives of this project, it is necessary to discuss the process of respiration in a more detailed manner. Milner and Geddes (1954) explained that respiration of the living cells may occur in aerobic or anaerobic conditions. Under aerobic conditions O₂ is absorbed and organic compounds particularly carbohydrates and fats, are oxidized with the formation of CO₂ and water as end products. For a typical carbohydrate (D-glucose) the respiration process is represented by the following equation:



Under anaerobic conditions, fermentation carried out by many microorganisms produces CO₂, ethyl alcohol and various acids. Under both conditions, CO₂ is produced and is commonly used as an index of gross metabolic activity.

It is convenient to compose the overall process of

grain respiration into two phases. In the first, organic compounds, specifically carbohydrate, are oxidized to CO_2 and five pairs of electrons in hydrogen atoms. The electrons are passed through a sequence of reactions, during which ATP (a coenzyme, major carrier of chemical energy) is re-generated from ADP (a coenzyme, regulator in cellular reaction) and inorganic phosphate. At the end of this sequence the hydrogen atoms are combined with O_2 to produce H_2O . These two phases of biochemical oxidation are shown in Figures 1 and 2. Aurand and Woods (1973) believe the main respiration occurs in three phases: (1) mobilization of acetyl-CoA from pyruvate (which comes from degradation of carbohydrate, fatty acids or amino acids), (2) the breakdown of acetyl residues by the tricarboxylic acid cycle (TCA) to yield CO_2 and H atoms, and (3) the hydrogen atoms removed during dehydrogenation are finally combined with molecular oxygen to form water (see Figure 2 for more details). Each mole of pyruvate mobilizes acetyl-CoA in TCA cycle and produces three molecules of CO_2 and five pairs of hydrogen atoms. One pair of hydrogen atoms is combined with O_2 and forms water which is used in TCA to keep this cycle in the active form, and one more pair of hydrogen atoms is used to reduce enzymes in the electron transport system. The combination of three pairs of remaining hydrogen atoms with oxygen forms three molecules of water. Considering the

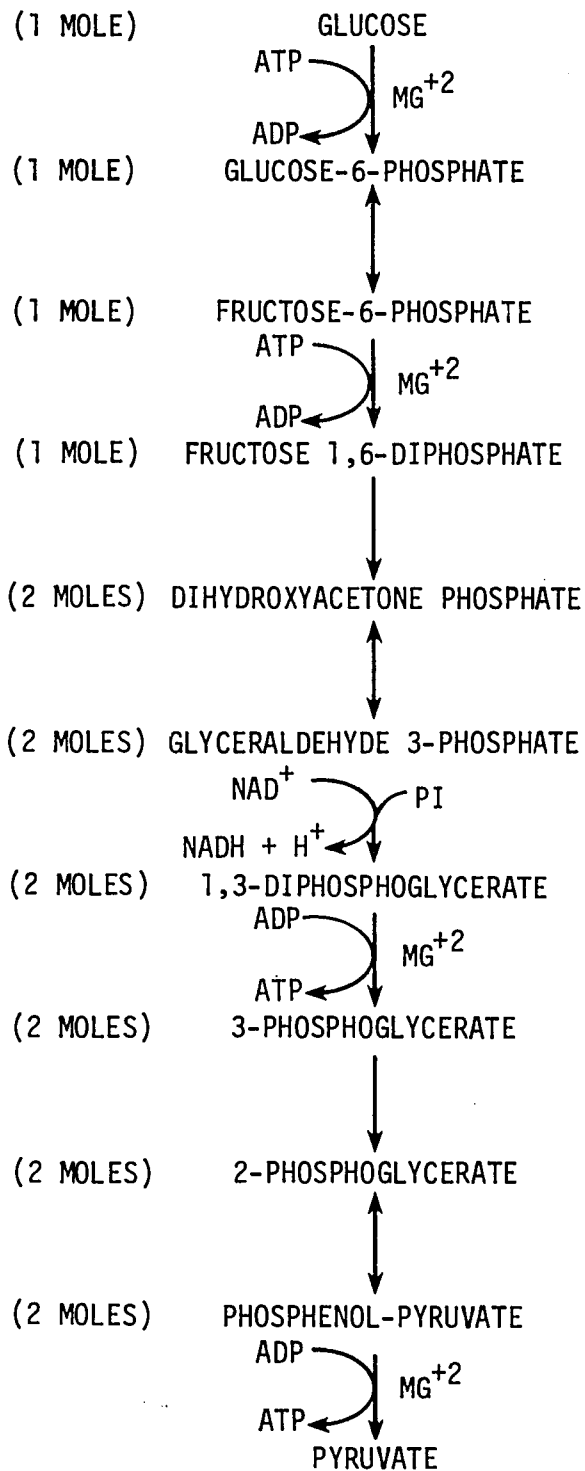


FIG. 1. GLUCOSE DEGRADATION VIA GLUCOLYSIS (DESCENDING REACTION)

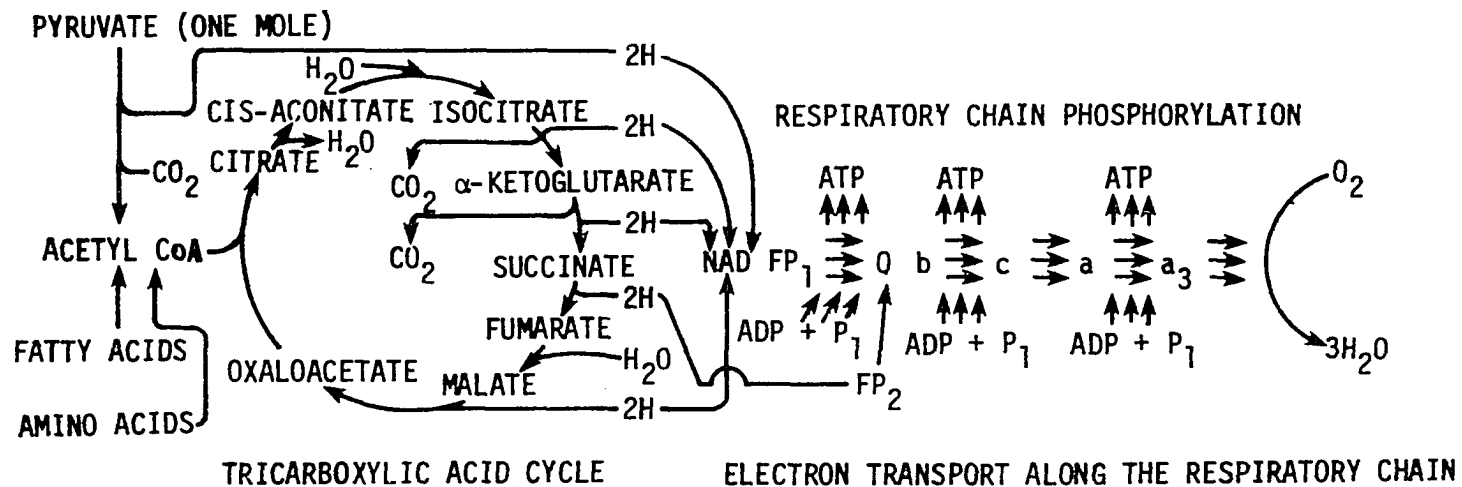
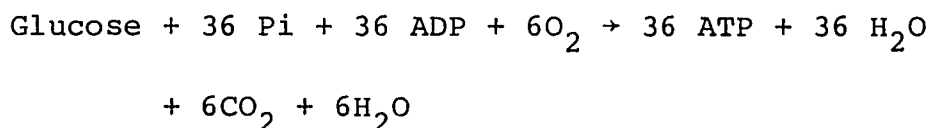


FIG. 2. HIGH-ENERGY ELECTRONS RELEASED IN OXIDATION OF CARBOHYDRATES, FATTY ACIDS, AND AMINO ACIDS DRIVE ADP PHOSPHORYLATION AS THEY MOVE THROUGH THE RESPIRATORY CHAIN: FP_1 (NADH₂), FP_2 (SUCCINATE DEHYDROGENASE), Q (COENZYME Q), b, c, a, AND a_3 (THE CYTOCHROMES)

fact that each molecule of glucose degrades to two molecules of pyruvate in glycolysis pathway, for biological oxidation of one molecule glucose, there would be six molecules of water and six molecules of CO_2 formed.

The end products of respiration, CO_2 and water, have far less utilizable free energy than fermentation products; e.g., alcohol has some nutritional value but water does not. Consequently, respiration potentially makes available much more energy for use by the cell than fermentation since $\Delta G = -686$ kcal/one mole of glucose reaction. As Bailey and Ollis (1977) reported, the actual energy yield of respiration can be estimated conveniently, by accounting for the number of ATP molecules regenerated per one glucose molecule in the following manner.



Since ATP hydrolysis has a standard free-energy change of -7.3 kcal/mole, the free energy of above-mentioned reaction is approximately

$$\begin{aligned} \Delta G^\circ &\approx (36 \text{ mol-ATP/mol glucose})(-7.3 \text{ kcal/mol ATP}) \\ &= -263^\circ \text{ kcal/mol glucose} \end{aligned}$$

Therefore, the energy capture efficiency for the

production of ATP is $\frac{263}{686} \approx 38\%$.

Most of the remaining energy is dissipated as heat which is dissipated to keep the temperature of the cell within a physiological range.

Although grain respiration is mainly due to storage fungi rather than the seed by itself, the cellular production by fungi is negligible. Most of the energy produced by the respiration is dissipated as a heat rather than production of ATP. Unfortunately, it is difficult to calculate the exact heat of respiration, and there is inadequate literature on this topic. One can assume respiration as a combustion of grain, in which carbohydrate, protein and fat oxidized to CO_2 , H_2O and heat. Since the main portion (75%) of shelled corn is carbohydrate and the rest are protein (10%) and fat (5%), and that the heat of combustion of these compounds are 4, 4 and 9 kcal/g, respectively, it is concluded that the heat of respiration for 1 g loss of grain is approximately 4 to 5 kcal/g of grain.

Effective Factors in Rate of Respiration

Environmental factors and the physical conditions of the grain have considerable effects on respiration rate of grain. Bartholomew (1965) reported the effects of moisture content, temperature, oxygen, time and the amount of

mechanical damage on the respiration rate of shelled corn. Respiration rates were reported to increase exponentially with an increase in moisture over the range of 4 to 13% moisture content. Respiration of live seed approximately doubled with each 10°C rise in temperature. He also reported: 1) the effect of temperature on the respiration rate became less marked after long storage periods, 2) high levels of oxygen inhibited respiration after long periods of storage, 3) for short storage periods, respiration increased with an increase in oxygen concentration and 4) moisture had no effect on CO₂ evolution from dead sterile seeds. Milner and Geddes (1954) indicated that physical damage to the seed coat from any cause, such as mechanical damage from harvesting, handling, or from insect attack, increases the storage hazard. They said frost-damaged seeds, even though of lower viability, respire more rapidly than sound seed. Steele (1967) graphically illustrated the expected independent effects of time, temperature, moisture content and specifically mechanical damage level on the CO₂ evolution or rate of respiration (see Figure 3). It should be noted that the relative importance of seed metabolism and that of microorganisms in grain deterioration can only be obtained by separating their activities. Steele (1963) found that seed respiration is a linear function of time and mold respiration is an exponential function of time. Milner and Geddes (1954)

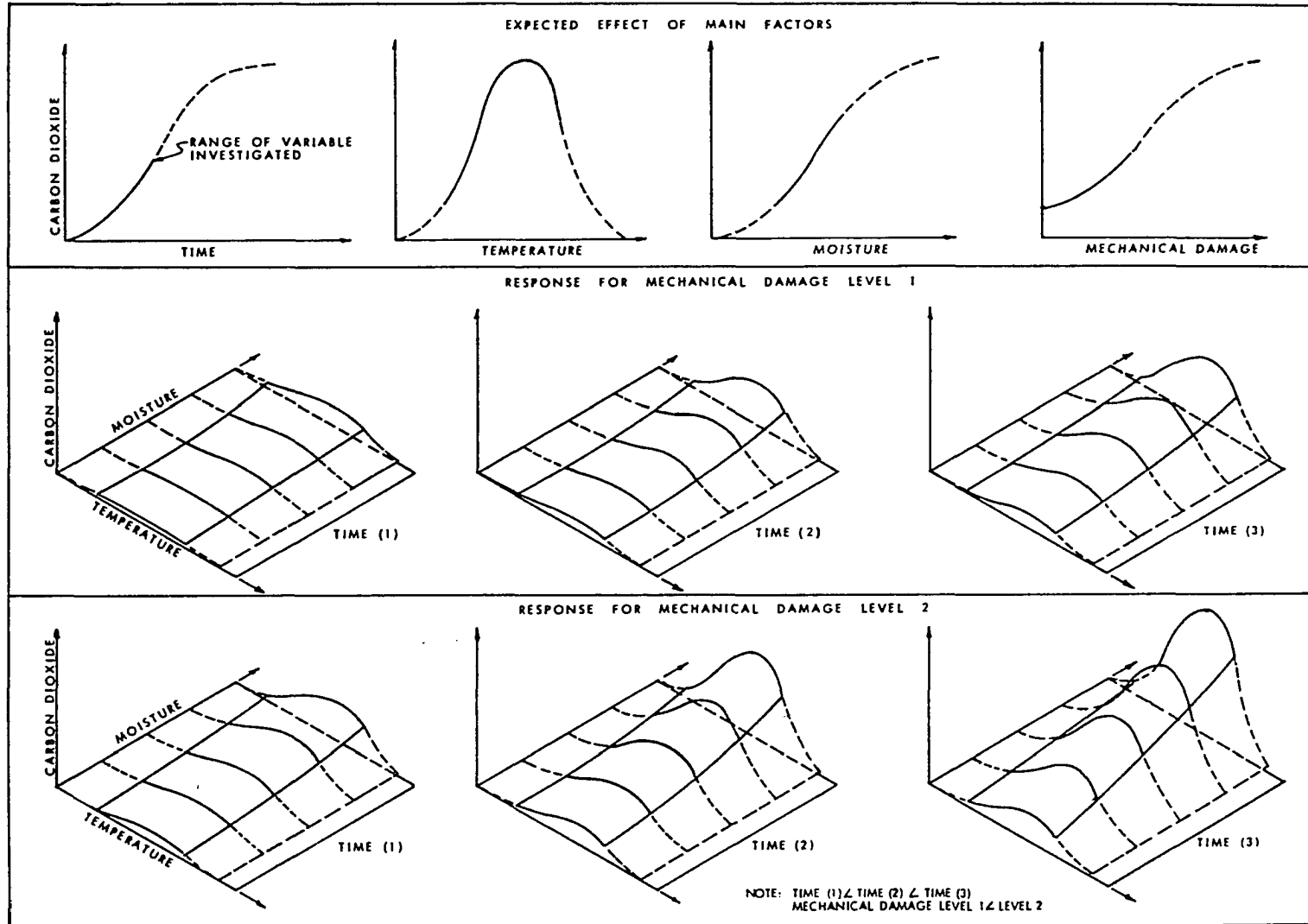


FIG. 3. EXPECTED CO_2 RESPONSE (STEELE, 1967)

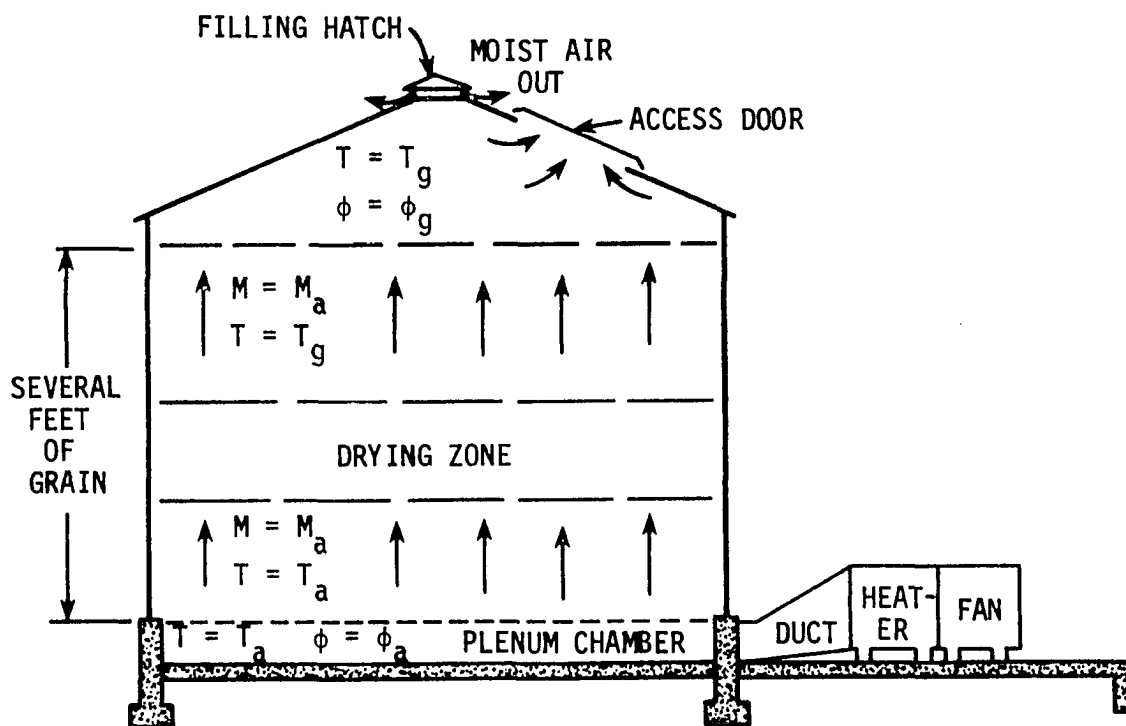
reported that the respiration of mold-free wheat at 35°C and moisture levels of 20 to 31% to be low and almost constant with time. In contrast, the respiration rates of moldy wheat increased with time.

Saul and Lind (1958) reported that a measured dry matter loss of 1.0 percent during drying and storage corresponded to oxidation of carbohydrate (glucose) and evolution of a total of 14.7 g of CO₂ per kg dry matter. They also found a close correlation between mold counts and total CO₂ per kg of dry grain. Since growth and development of microflora and specifically molds depends heavily on moisture content, grain temperature, grain quality and available O₂, there is no doubt that favorable conditions of these factors enhance the biological activity of the microflora associated with the grain itself, grain drying and handling equipment and cause grain deterioration.

Grain Drying

One of the practical ways to reduce the growth of molds is drying of grain from a high moisture content to a safe moisture content. In low temperature or natural air drying of wet grain with a good management system there is a good potential of having a lower cost per unit weight and a better quality in comparison with high temperature drying. In a low temperature drying bin a drying zone (a layer of grain

where drying is taking place) forms at the air entry side of the grain mass and progresses through the grain in the direction of air movement until drying is complete. As Figure 4 shows there is a "wet zone" in the top of "drying zone". Brooker et al. (1974) indicated that the grain below the drying zone has essentially reached equilibrium conditions with the incoming air and has a moisture content of M_e . They also noted that air passing through the grain above the drying zone is in equilibrium with the initial grain moisture content, M_o . Air passing through the drying zone takes moisture from the grain by evaporation and is cooled by the evaporation process from T_a (air temperature) to T_g (grain temperature). Hukill and Shedd (1955) and Saul (1960) demonstrated that little or no drying takes place within the wet zone above the drying zone. Hukill (1947) also pointed out that the grain drying process is one of constant total heat, and that with some exceptions, the wet bulb temperature of the entering air and of the exhausted air are equal. Saul (1960) concluded that the in-storage drying process is an adiabatic saturation of the drying air. Because of high relative humidity and moisture content of grain at the top zone of grain, considerable biological activity (respiration of grain and microflora) is present during grain drying and will result in grain spoilage unless heat and airflow pick up the moisture and remove the



M = MOISTURE CONTENT
 M_a = AIR MOISTURE CONTENT
 M_g = GRAIN MOISTURE CONTENT
 T = TEMPERATURE
 T_a = AIR TEMPERATURE
 T_g = GRAIN TEMPERATURE
 ϕ = RELATIVE HUMIDITY
 ϕ_a = AIR RELATIVE HUMIDITY
 ϕ_g = GRAIN RELATIVE HUMIDITY

FIG. 4. A FIXED-BED DRYING PROCESS AS IT OCCURS IN A FULL-BIN SYSTEM (BROOKER ET AL. 1974)

generated heat of respiration from the top of the bin.

Foreign and fine materials have an important role in grain contamination during storage and performance of grain drying in the bin. Cleaning of grain is not only desirable but it is highly recommended for corn before low temperature drying or storage. During cleaning, straw and chaff, other crop seeds, light kernels, diseased or damaged seeds, insects and other impurities are eliminated. The cleaning process of grain has the following advantages:

1. It provides grain with a better and higher quality and enhances marketing of the grain.
2. Since fines in the corn are the most susceptible to spoilage, removing these materials minimizes the contamination of grain in the bin.
3. Removing as many fines as possible permits air to pass through the corn more easily. In other words, cleaning provides a more uniform product through which to move air. Brooker et al. (1974) explained the air flow resistance of a mixture of fines and clean corn. He pointed out that as the percent of fines in the mixture increased, the resistance pressure increased, reaching a maximum when there were 30 to 40% fines present. They also said that maximum pressure drops were approximately double those for clean corn. Shedd (1953) indicated that fines and foreign materials finer than the grain will pack the grain and causes higher (50% or more) resistance to airflow.
4. Cleaning of grain is desirable before drying and/or storage. During cleaning, straw and chaff, other crop seeds, light kernels, diseased or damaged seeds, insects, and other impurities are eliminated.

In order to show the effects of spoilage on different parts and components of grain, it is appropriate to discuss

first the anatomical structure and chemical composition of the corn kernel.

Corn Kernel, its Size, Anatomical Structure and Chemical Composition

The size and weight of corn kernels not only vary among different varieties of corn but also among the kernels of the same ear of corn. Typically, the kernels at the two ends of the ear are smaller and round in shape compared to the kernels from the midsection of ear. The grains of corn kernels which sometimes are referred to as naked caryopses (pericarp and seed), are comprised of a seed coat, germ and endosperm. The principal parts of a dent corn kernel are shown in Figures 5 and 6. A single seed of the naked caryopses is enclosed by a thin pericarp, under which lies the seed coat. The aleurone layer lies under the seed coat and in part of the endosperm. The corn kernel consists of two kinds of endosperm, the floury endosperm and horny endosperm. The floury or starchy endosperm, which is light in color, contains loosely-packed starch granules with little protein. The horny endosperm which is more intensely colored in yellow varieties, has smaller starch granules. The cells of the horny endosperm are filled with starch granules in a protein matrix. The germ consists of the scutellum, plumule and radicle. The mechanical properties of the different parts of the kernel are not the same. According

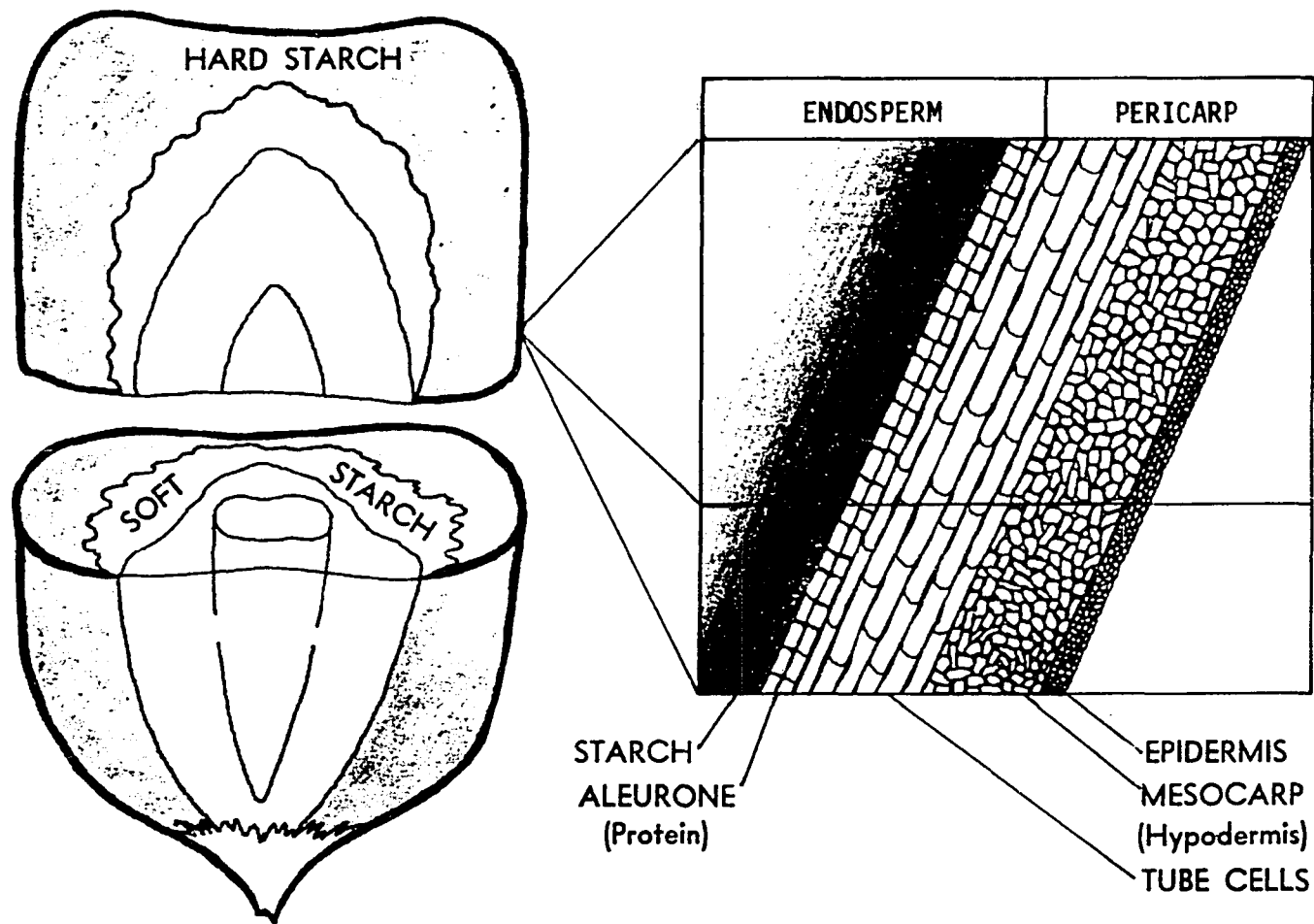


FIG. 5. CROSS SECTION OF A SEED COAT IN CORN KERNEL (WOLF ET AL., 1952)

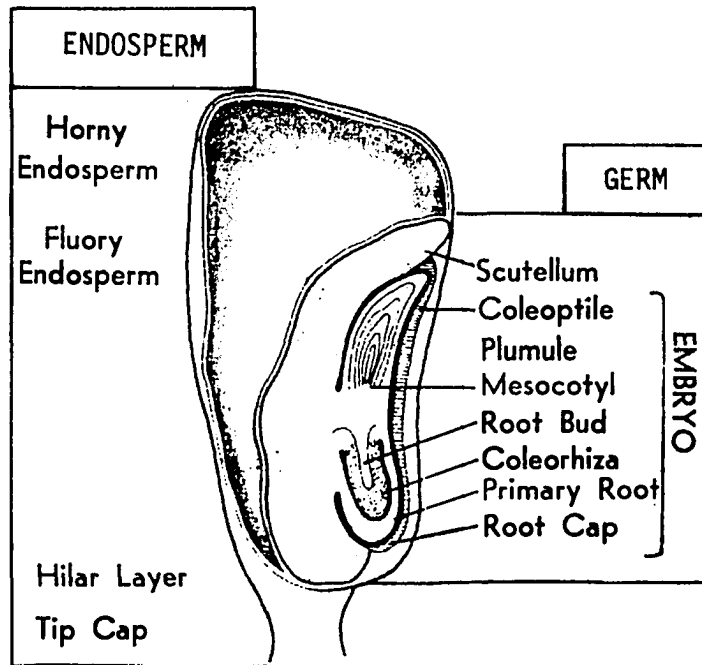


FIG. 6. ENDOSPERM AND GERM STRUCTURE IN CORN KERNEL (WOLF ET AL., 1952)

to Chowdhury and Buchele (1975), the embryo is the softest part compared with the endosperm and horny endosperm.

The proportion of different parts (hull, pericarp, aleurone layer, endosperm, embryo and scutellum), for a corn kernel varies with different varieties and the level of maturity. Earle et al. (1946) reported that the whole corn kernel is comprised of the endosperm (82 percent), the germ (12 percent), the pericarp (5 percent) and the tip cap (1 percent) of the kernel mass.

Mature corn, like other cereals, consists of carbohydrates (soluble and insoluble), nitrogenous compounds (mainly protein), fat, mineral salts and water together with small amounts of vitamins, enzymes and other substances. The chemical composition of corn kernels varies not only with different varieties of grain and level of maturity but it also varies among different parts of the same grain kernel. Table 2 shows the average composition of whole corn and hand-dissected fractions (moisture free basis) as collected by Earle et al. (1946).

Table 2. Average composition of whole corn and hand-dissected fractions
(Earle et al., 1946)

Fraction	Kernel (%)	Starch (%)	Protein (%)	Lipid (%)	Sugar (%)	Ash (%)
Whole grain	-	71.5	10.3	4.8	2.0	1.4
Endosperm	82.3	86.4	9.4	0.8	0.6	0.3
Germ	11.5	8.2	18.8	34.5	10.8	10.1
Bran	5.3	7.3	3.7	1.0	0.3	0.8
Tip cap	0.8	5.3	9.1	3.8	1.6	1.6

Losses Due to the Damage and Deterioration

Deterioration, or the respiration and enzyme activity of microflora associated with damaged corn while stored at unsuitable conditions, has considerable effects on chemical composition, physical properties, and physiological properties of the corn kernel. Perhaps the most important effects of mechanical damage (as related to grain deterioration) are as follows: 1) Earlier studies of Zeleny (1954) on changes in carbohydrate indicated that alpha- and beta-amylases attack the starches (nonreducing sugars) of grain and grain products during storage, converting them into dextrins and maltose (a reducing sugar). The conditions that favor starch decomposition usually favor respiratory activity also, so that the sugars are consumed and converted into CO_2 and water. Under these conditions, which usually occur at moisture level of 15% or more, the grain loses both starch and sugar and the dry weight decreases. Bottomley et al. (1952) demonstrated a marked disappearance of nonreducing sugars in corn stored under conditions favoring deterioration. Proteolytic enzymes in grain and in organisms associated with grain hydrolyze the proteins into polypeptides and finally to amino acids, (again at the conditions favorable to deterioration) and reduce nutritional value of protein. Daftary et al. (1970) found that because of respiratory losses of carbohydrates, the protein content of mold-damaged grain is

slightly, but consistently, higher than in the corresponding sound grain. These results indicated damage to proteins, in addition to breakdown and changes in lipids. Vitamin and fat content are reduced by mold and enzyme activity during grain spoilage. Considerable losses of vitamin A and tocopherols have been shown to occur in yellow corn during storage. According to Pomeranz (1974), losses of total carotenoid pigments, not rapid during the early part of storage periods, were approximately a logarithmic function of time, and temperature exerted more effect than moisture content. Losses of tocopherols are accelerated in grain stored under adverse conditions (Karp 1959). 2) Another serious problem, associated with corn quality, and one important to the livestock feeder, is the presence of mold capable of producing toxins in the feed. Cracks and breaks in the pericarp of kernels provide an excellent habitat for the growth of molds. Christensen and Kaufmann (1969) showed that, in a stress condition of growth, the mold Aspergillus flavus produces a carcinogenic substance known as aflatoxin. According to Food and Drug Administration regulations, the presence of aflatoxin in a shipment may result in the material being seized and destroyed. Corn which contains more than twenty parts-per-billion of aflatoxin cannot be used in products intended for human consumption. The standards on corn used in animal feed vary with allowable

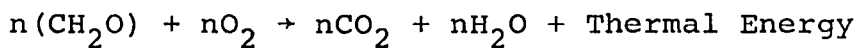
aflatoxin levels between twenty and one-hundred parts-per-billion (Risser 1977). Van Womer (1972) reported that in the fall of 1971 alone, the FDA seized 81,720 kg of corn meal made from aflatoxin-tainted white corn. Recently, Bennett and Shotwell (1979) recognized the toxin of zearalenone in contaminated corn and other cereal grain. Zearalenone, a secondary metabolite with estrogenic properties is produced by several fusarium species that colonize cereal grains in the field and in storage. 3) Mechanical damage also adds to the cost of handling and processing of corn. The dry and wet milling industry has reported a reduction in both the quantity and the quality of the final products with an increase in mechanical damage to the grain. Zeleny (1954) indicated that there is difficulty in separation of starch from other components of corn during wet milling process. Freeman (1972) reported that corn, damaged during harvesting, drying, storage, or handling, can reduce production capacity of the wet milling plant and result in reduced yields of primary products and impair the quality of the products. According to Chowdhury (1978), the grain damage is a cause of poor millability, low oil recovery, low starch viscosity and low pigment content of gluten. Roberts (1972b) explained that the dry millers are losing nearly one million dollars annually as a direct result of mechanical damage of corn kernels. One of the major products of dry

millers is the flaking grit, used for the production of popular breakfast cereal, corn flakes. Fractures and fissions in the corn kernels results in the split and fractured grits, which result in smaller corn flakes, a less desirable product. Production of corn flakes requires corn that is free from severe mechanical damage. 4) Fats in grain are readily broken down by lipases into free fatty acids and glycerol during storage, particularly when temperature, moisture content and damage level are high and thus favorable to general deterioration. According to Pomeranz (1974), this type of change is greatly accelerated by mold growth because of high lipolytic activity of the molds. Fat hydrolysis takes place much more rapidly than protein or carbohydrate hydrolysis in stored grain. This is the reason that the free fatty acid content of the grain has been proposed as a sensitive index of incipient grain deterioration. Bailey (1964) reported that there would be a higher loss in refining oil due to an increase in fatty acid content of vegetable oil. 5) Mechanical damage also decreases seed corn viability and results in lower yield. Gomez and Andrews (1971) reported that root growth rate and germination was drastically reduced because of the injured seed corn. Certain mechanical injuries cause immediate loss of viability. Injuries near the point of attachment of the cotyledon to the embryonic axis, or on most other viable parts of embryonic axis, usually

bring about a rapid loss of viability during storage (Roberts 1972a). 6) Mechanically injured seed may cause direct financial loss from production to consumption, to the farmer, grain buyer, shipper and processor. Kaminski (1968) estimated that the quantity of fines produced by mechanical damage had a market value of three cents per bushel. Mechanically damaged corn has not only a lower market value and lower potential, but also a lower export appeal. Bailey (1968) mentioned that American farmers lose up to four cents per bushel on all the corn sold because of broken kernels.

Oxygen Utilization of the Shelled Corn

Respiration is a physiological process through which living cells and organisms utilize chemically bonded energy (sugars) of grain to promote the biological functions involved in sustaining and promoting a life system (metabolism). The general chemical formula for respiration is:



The above formula shows that the grain endosperm is a storehouse of food ^{and} can be consumed but once. In the case of damaged grain, there is no resistance against consumption of this food by living organisms. Of course conditions such as accumulation of warmth and moisture in the grain accelerates metabolic processes in the seed and promotes parasite

activity. These living organisms such as molds or bacteria consume it before man or animals. Obviously, because of economical and nutritional values, the object of cultivating and preserving grain is as a food source for man or animals.

It is possible to measure the oxygen transfer rate of the grain during respiration and evaluate the conditions to minimize the rate of respiration. At the same time we like the conditions for grain storage to preserve the viability of the grain and to avoid killing the grain by freezing or high temperature drying especially if the grain is intended for seed purposes.

The oxygen utilization rate can be measured in a batch system with no additional or removal of liquid or gas by monitoring gas volume or pressure changes with time. An early device for monitoring oxygen consumption was a constant-volume respirometer which Warburg in 1926 devised from earlier similar manometric devices of Barcroft and Haldane (1902) and Brodie (1910). In this device a small volume flask is attached to a U-tube manometer. The flask has space for the sample solution, a small open cylindrical reservoir for an alkaline CO_2 absorbent, and a side arm used later to add another component to the initial solution. During a measurement, the manometer fluid in the closed manometer leg rises due to the oxygen consumption of the

sample. Periodic changing of the open manometer tube position restores the closed-leg meniscus to its original level. The resulting height difference between the manometer legs provides a measure proportional to the pressure change of the constant volume system. The alkali, e.g., KOH, in the separate reservoir communicates only with the gas phase; it rapidly absorbs all the CO_2 liberated from the respiring solution. Since there is a gas-liquid mass transfer resistance at the interface of the solution and gas, a minimum shaking rate is needed to eliminate this problem. In this system, the net oxygen utilization rate can be calculated according to the following formula:

$$\frac{\Delta n}{t} = \left(\frac{V_g + V_f M}{RT} \right) \frac{h}{t} = b \frac{h}{t}$$

where

Δn = total oxygen uptake in mols

t = respiration time in min

V_g = volume of gas in μL

V_f = volume of sample fluid in μL

M = Henry's Law constant

h = pressure difference across the manometer leg in atmospheres

R = universal gas constant

T = temperature of solution, $^{\circ}\text{K}$

b = flask constant

Since measuring oxygen consumption rate with the original Warburg respirometer is not an easy job and needs a lot of considerations, Gilson in 1963 made a modified instrument of Warburg respirometer with the following advantages:

- (1) a digital reading is obtained directly in microliters;
- (2) calibration of a glassware and evaluation of "flask constant" is not necessary;
- (3) the manometers are stationary, and easily read;
- (4) all manometers are simultaneously visible;
- (5) spring-loaded valves have definite stops for off and on positions;
- (6) valves may be simultaneously operated by levers for opening and closing; and
- (7) a very solid construction can be readily employed.

A constant pressure system has been used in respirometry for many years. Gregory and Winter (1965), recommended the use of constant-pressure respirometer. They did a lot of studies on this kind of respirometer in order to simplify an equation which relates observed volume change to the actual change in amount of assayed gas, expressed as μL at standard conditions. They also suggested the following equation for correction to standard conditions of the observed change in gas volume while ignoring the solubility of gases in the barometric fluid:

$$X = \Delta V_g \frac{(P - P_w)}{P'} \cdot \frac{T'}{T}$$

where

X = total amount of gas being measured, expressed as volume at standard conditions, μL

ΔV_g = observed change in volume of respirometer, μL

P = total gas pressure within the respirometer, mm Hg

P_w = vapor pressure of water at temperature T , mm Hg

P' = standard pressure, 760 mm Hg

T = temperature of water bath, $^{\circ}\text{K}$

T' = standard temperature, 273°K

According to Umbreit et al. (1957) the limitations of the Warburg respirometer are:

1. The gases exchanged must be only O_2 and CO_2 . In most cases this condition is not difficult to meet since in the majority of biological samples these are the only gases involved.

2. The rate of oxygen uptake, and the rate of CO_2 liberation and absorption must be within a particular range so that the assumptions of the method hold, i.e., that the fluid (water in case of grain respiration) is always saturated with oxygen gas (or air) and that the pressure of CO_2 in the gas phase approximates zero.

Oxygen consumption of the seed is directly related to the water content of the seed. In dry seed it is almost impossible to measure oxygen uptake rate or CO_2 output.

The change in the O_2 uptake CO_2 output and the respiratory

quotient $R.Q. = CO_2/O_2$ is dependent of the state of oxidation or deterioration of different seeds. Mayer and Poljakoff-Mayber (1975) mentioned that highly oxidized substrates such as organic acids result in R.Q. of between 1.0 and 1.5 while fats give R.Q.'s of the order of 0.7-0.8. As they showed an R.Q. of 1.0 is characteristically obtained if substrate respired is a carbohydrate.

As it was noted before, with the increase in moisture content, the level of gas exchange increases too. Bailey (1921), showed that in Zea mays seeds and other cereals (sorghum, wheat and rice) the output of CO_2 rose from 0.7 mg per 100 g dry weight during 24 h, when the seed had a moisture content of 11%, to about 60 mg when the moisture content was 18%.

Documented literature such as Mayer and Poljakoff-Mayber (1975) indicated that on moistening seeds with water, there is an immediate gas release which seems to be a purely physical process and is not related to respiration of the seed. Haber and Brassington (1959) supposed that the liberated gas is colloiddally absorbed within the seeds.

Relation of Corn Seeds and Water

Many experiments have been done to show the effect of water uptake rate of the seed during the course of pre-germination, but few references are available describing

the relation between water utilization rate and the physical properties of the seed, such as the level of mechanical damage of corn kernels.

Utilization of water by the seed (before germination) is commonly called an imbibition process. This phenomenon is a physical process which is related to the properties of colloids and is no way related to the viability of the seeds (Mayer and Poljakoff-Mayber 1975). In other words, it occurs equally in live seeds and in seeds which have been killed by heat or by some other means. The extent to which imbibition or water uptake occurs is determined by three factors, the composition of the seed, the permeability of the seed coat to water, and the availability of water in liquid or gaseous form in the environment.

In seeds the chief component which imbibes water is the protein. The mucilages of various kinds will contribute to swelling, as part of the cellulose and the pectic substances. Starch, on the other hand, does not add to the total swelling of the seeds, even when large amounts of starch are present. As Mayer and Poljakoff-Mayber (1960) remarked, the swelling of seeds therefore reflect, to some extent, the storage materials present in the seeds.

The second factor which has effects on the entry of water into seeds is the permeability of the seed coat. Seeds which are surrounded by an impermeable seed coat will

not swell under otherwise favorable conditions. The impermeability of the seed coat (usually a multi-layered membrane containing a number of layers or cells), or its selective permeability is frequently the cause of dormancy. Various external factors can cause changes in the permeability of the seed coat. Heat-killed seeds often imbibe water more rapidly than the corresponding viable seeds probably because the permeability of the seed coat is increased by the heat treatment (Mayer and Poljakoff-Mayber 1975). As Bonner (1968) showed, the pericarp in the seeds is normally impermeable unless it is damaged by some external factors. This is the reason that damaged seed has a higher rate of water uptake than whole sound seeds. Chung and Park (1971b) studied the absorption kinetics of water vapor by sound and various damaged grains at several environmental conditions and examined the possibility of evaluating grain with external damage by the water absorption rate. This was a good reason for us to examine the effect of internal damage of corn on its rate of water uptake.

Besides the degree of damage, the water absorption rate depended considerably upon the initial moisture content, temperature and the history of the grain.

Besides the fact that seeds increase their volume to some extent when they are in contact with water, the heat generation is another phenomenon which is caused by water

uptake process. Many people believe that the formation of hydrogen bonds with carbohydrate and protein molecules is a cause of heat production. This is probably very important in management of low temperature drying. When there is not enough air flow to remove the moisture from the grain, and the grain in upper layer is dryer than in the bottom layer, some of the water vapor from the drying zone may accumulate on the top of the bin, and because of the above-mentioned phenomenon, considerable heat is produced which favors the growth of fungi and deterioration of the grain.

PROCEDURE

Sample Preparations

Approximately 150 kg of yellow dent corn (Northrup King SX50) were obtained from the Agronomy-Agricultural Engineering Research Center west of Ames during fall 1977. Of this, 75 kg were ear corn, and 75 kg were shelled corn. Initial moisture content of the shelled corn was read by a Motomco moisture tester and it was roughly 26% wet basis. The shelled corn was harvested by using a John Deere Model 55 3-row conventional combine. Enough ear corn was husked and shelled to get approximately 4.50 kg of hand-shelled corn. Each corn ear has various sizes and forms of kernels. Ordinarily, uniform kernels are in the midsection but small and round kernels are near the ends of the cob. Approximately 7 kg of uniform hand-shelled corn were acquired by husking ear corn and cutting off both ends of the ears by using a Wellsaw Model 300 band saw. The ear ends were discarded, and the midsections, which amounted to 60 to 70% of the ear, were retained. These ear midsections were hand shelled. We attempted to shell only the uniform kernels which weren't damaged after cutting with the electric saw. Figure 7 illustrates this treatment.

Three 200-g random samples from the mass of hand-shelled and three 200-g random samples from the mass of machine-shelled corn were obtained and moisture content (wet basis)

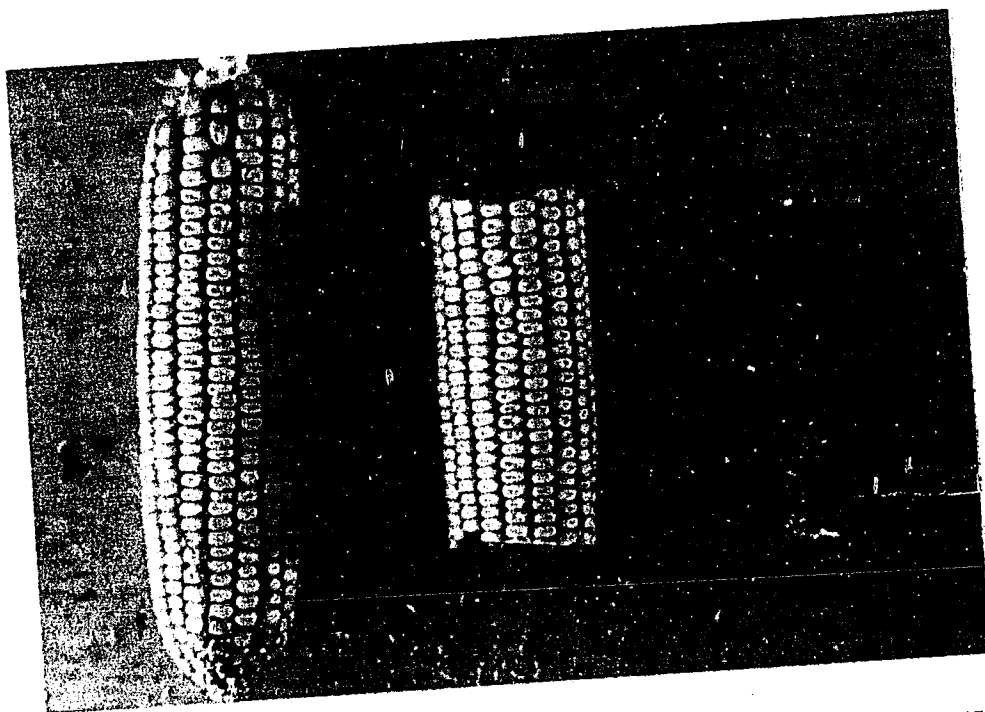


FIG. 7. WHOLE EAR CORN AND 70% OF MIDSECTION OF CORN COB WITH
UNIFORM KERNELS BEFORE AND AFTER SHELLING

was determined by the standard AOAC air-oven method (AOAC 1950). Again, enough machine-shelled corn (approximately 25 kg) was hand-picked kernel-by-kernel to get at least 9 kg of the kernels with no visible damage and 4.5 kg of damaged kernels. Figure 8 shows the separation of hand-shelled corn into uniform and nonuniform (smaller round) corn kernels and machine shelled corn into damaged kernels and corn kernels with no visible damage. According to the American Society of Agricultural Engineers standard: ASAE S343, about grain damage definition (Agricultural Engineers Yearbook 1977), the resulting damaged corn and uniform hand-shelled corn were mixed in specific ratios to get 0, 25, 50, 75 and 100% damaged corn (see Table 3).

Damaged corn in our experiment is defined as corn having many different levels of visible damage. To get some approximation of damage level, three random samples were obtained from the machine-shelled corn and analyzed according to the method described by Chowdhury and Buchele (1976a).

To see the effect of cleaning, three random samples were obtained from the machine-shelled corn, and broken and fine materials were removed by using a 4.76-mm (12/64-in.) round-hole sieve. The foreign material was hand-picked from the top of the sieve and discarded. At the same time, 1.50 kg of uncleaned corn was randomly obtained from the machine-shelled lot.

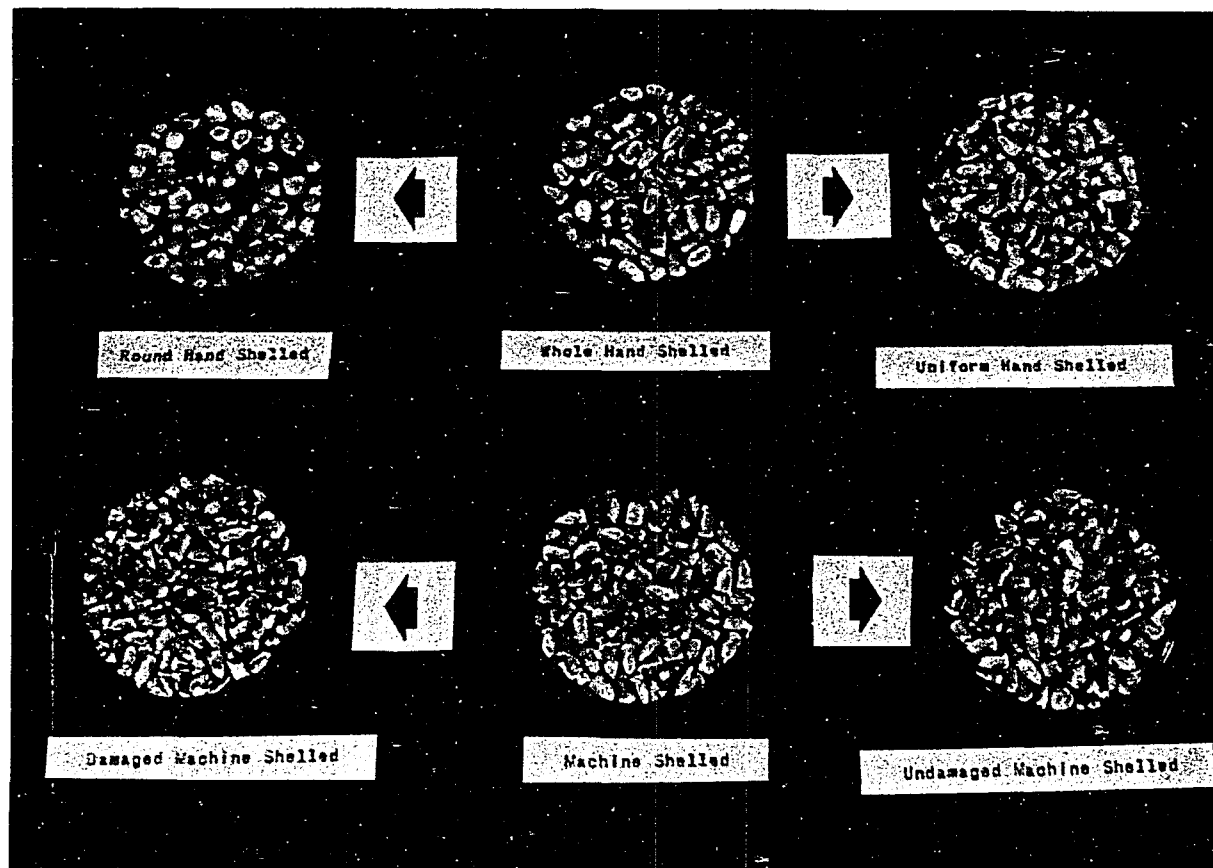


FIG. 8. TOP: WHOLE HAND SHELLLED IS THE COMBINATION OF UNIFORM HAND SHELLLED AND ROUND HAND SHELLLED CORN
 BOTTOM: MACHINE SHELLLED IS THE COMBINATION OF UNDAMAGED MACHINE SHELLLED AND DAMAGED MACHINE SHELLLED

Table 3. Ratios of mixing damaged portion of machine-shelled with uniform hand-shelled corn

Sample	kg damaged portion of machine-shelled corn	kg of uniform hand-shelled corn
0% damage	0.00	3.00
25% damage	0.75	2.25
50% damage	1.50	1.50
75% damage	2.25	0.75
100% damage	3.00	0.00

The portion of machine-shelled corn with no visible damage was checked under a dissecting microscope (0.7X-3X magnification) and was divided into two portions. The first portion had tiny pericarp breakage (external damage) and supposedly some internal cracks. The second portion did not show external damage, but internal cracks were possible. From each portion, about 2.7 kg were prepared. The first portion is referred to as an invisible external and internal damage corn, the second portion as undamaged machine-shelled (internal cracks only) corn.

CO₂ Production Experiment

Steele (1967) used laboratory equipment to measure the production of CO₂ from small samples of shelled corn. The same system (with some modifications and improvement) was used here.

One of the most important functions of the equipment is the duplication of environmental conditions of grain above the drying zone in a bin in which drying is in progress. If the grain is at 25% moisture or above, according to equilibrium moisture content curves for shelled corn (desorption) from Rodriguez-Arias (1956), its temperature is the wet bulb temperature of the entering air. In this study, the temperature of the grain was held constant at 25°C.

The entering air had to be conditioned before entering the grain so as to maintain constant wet bulb temperature, relative humidity, and moisture content for grain. Figure 9 is a schematic diagram of the system for conditioning air and CO₂ absorption. Atmospheric air was supplied by an air compressor, and the volumetric flow rate adjusted by a pressure regulator valve. Then air was washed in a closed plastic container of water to eliminate dust and suspended particles that might be brought to the line by the air compressor. In the next step, CO₂ available in the entering air was removed by bubbling the humid air through a column con-

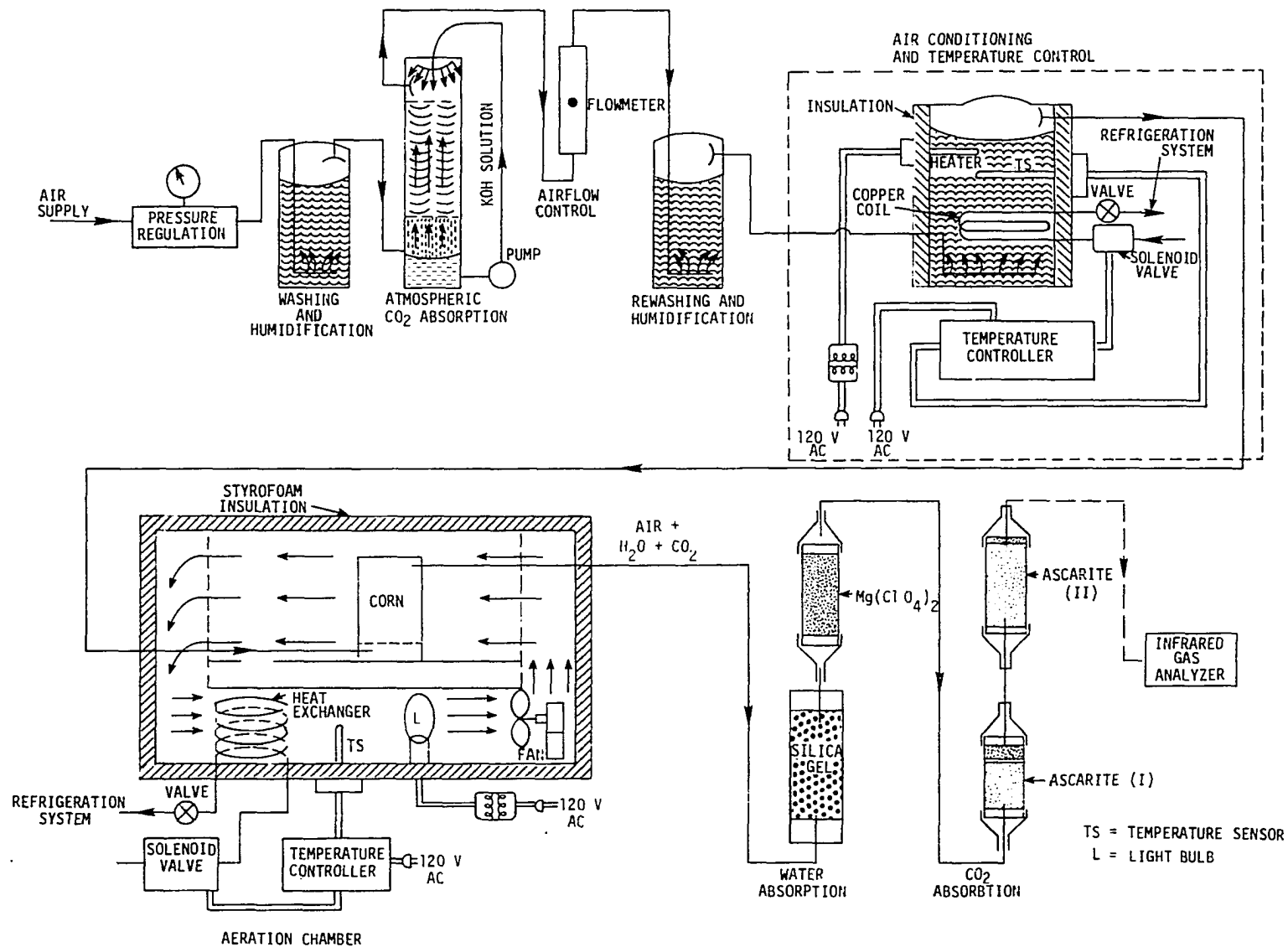


FIG. 9. SCHEMATIC DIAGRAM OF GRAIN AERATION CHAMBER AND CO₂ RECOVERY SYSTEM

taining a 30% solution of potassium hydroxide. The tower was equipped with a pump, which could circulate the potassium hydroxide solution in a direction opposite to that of the airflow. Volumetric airflow could be measured by reading a flowmeter. In this test, the airflow was about 1000 mL/min for each sample of 450 g (2 cfm/bu). Again, the air was washed in a closed plastic container to remove any potassium hydroxide. Although the air was washed in this stage, the air temperature had yet to be adjusted to meet the requirement for constant wet bulb temperature. For this reason, in the next stage, the humid air was washed in another closed water container equipped with an electric heater and a copper coil heat exchanger for cooling. The constant temperature of 25°C was maintained by circulating brine solution as a refrigerant through a copper coil placed in the tank, or, when needed, operating a submersible electric heater. The temperature was controlled by a mercury thermoregulator, which either actuated a solenoid valve permitting a refrigerant to flow through the copper coil or energized the electric heater. Next, the air passed through jars of grain in the air chamber (see Figure 10). The air chamber was equipped with the same system of a copper coil heat exchanger, electric heater, and temperature sensor, and temperature was regulated by the same process as was explained in previous steps. The only difference was that a light bulb was used as a source of heat,

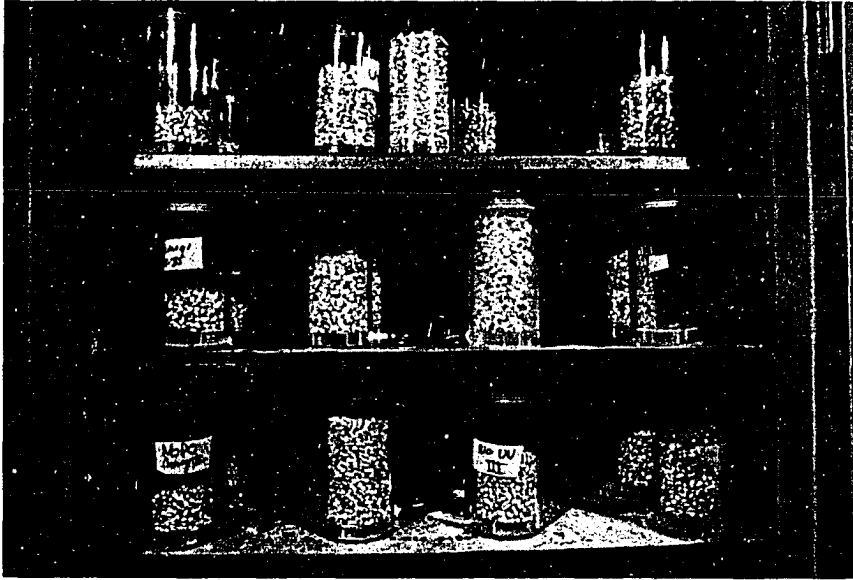


FIG. 10. JARS OF SHELLED CORN IN THE AIR CHAMBER

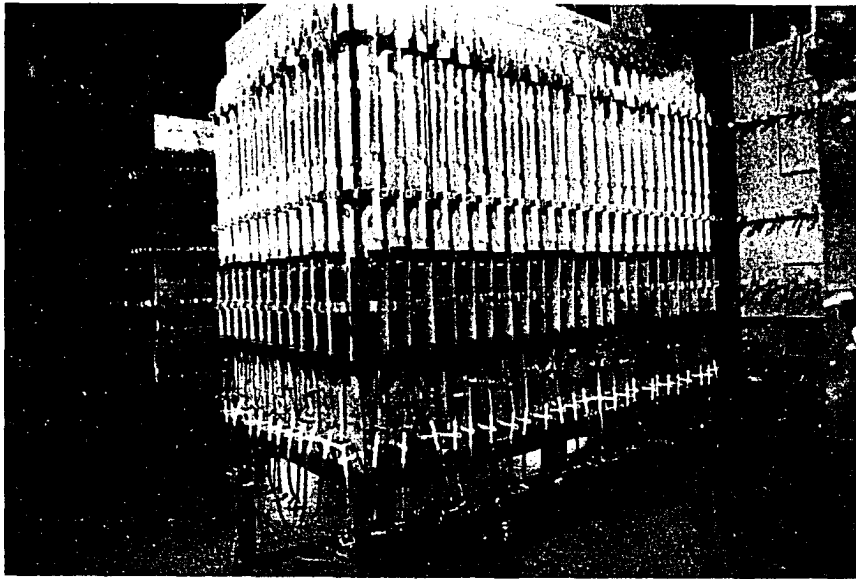


FIG. 11. TUBES OF (FROM BOTTOM) SILICA GEL, $\text{Mg}(\text{ClO}_4)_2$, ASCARITE, AND ASCARITE FOR ABSORPTION OF H_2O , H_2O , CO_2 , AND CO_2 , RESPECTIVELY

and a small fan circulated air to maintain a constant temperature of 25°C throughout the chamber. The chamber was covered with 7.5 cm of styrofoam insulation to minimize temperature variations. The air, which continuously aerated the grain, carried out CO₂ and water vapor produced by the respiration process. In the following step, the major portion of water vapor was absorbed by silica gel, and the traces of water left in the stream were absorbed in the subsequent tube containing magnesium perchlorate. Finally, the CO₂ was absorbed in a series of two tubes containing ascarite. The major portion of CO₂ was absorbed by first tube, and the remaining portion absorbed in second tube. Figure 11 shows the way silical gel and ascarite tubes were connected together and absorb water and CO₂ respectively. Periodically, an air flow meter was connected to the top of the second ascarite tube to make sure that adequate air flow was passing through the jar of grain and that there was no obstruction in the system (see Figure 12). The second tube of ascarite was attached to a gas analyzer periodically to see if traces of CO₂ were escaping from the tube without being absorbed by the ascarite. Ascarite is a granular composition of asbestos particles coated with a layer of sodium hydroxide and has a relatively high CO₂ absorption capacity. As Figure 11 illustrates, the color change of these chemicals is a good indicator of saturation and determines the right time for replacement.

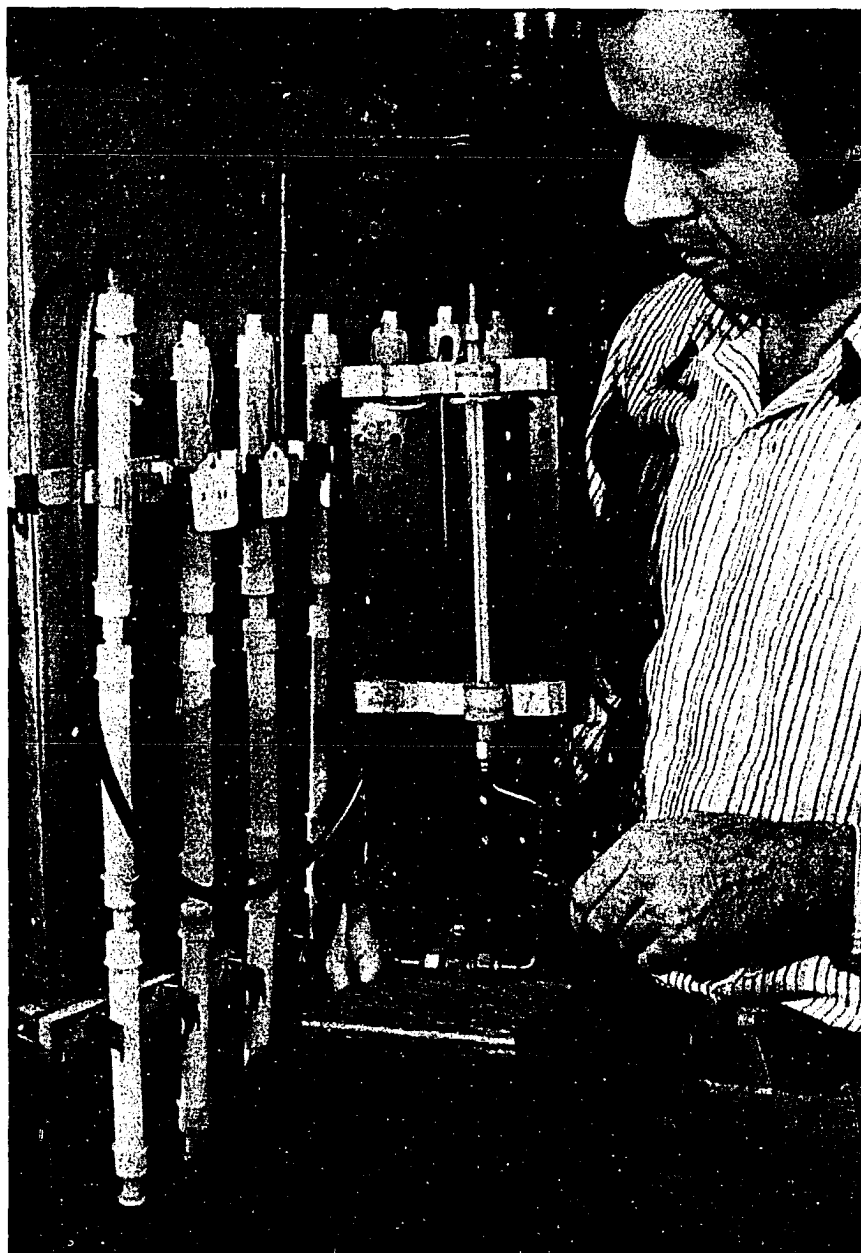


FIG. 12. CHECKING GAS FLOW IN THE SYSTEM BY CONNECTING FLOWMETER TO TOP OF SECOND ASCARITE TUBE

The ascarite tubes were weighed by using a Metler analytical balance at approximately 24-h intervals. The chemical was replenished before it had absorbed 2% of its weight in CO_2 and, in many instances, much sooner even though ascarite had the capacity to absorb 20-25% of its weight. The Metler analytical balance used was a fast-reading type, with an accuracy of ± 0.25 mg.

The major modification and advantages of this CO_2 absorption system, in comparison with Steele's system, were:

1. Use of an air chamber as an outside environment for grain jars instead of a water bath. Precision controls for the system were added.
2. Use of an infrared gas analyzer in the top of the second tube of ascarite to detect possible CO_2 leakage.
3. Use of a smaller quantity of ascarite for CO_2 absorption (about one-third of total ascarite that Steele used).

The following 454-g samples were prepared in the jars and placed in the air chamber for the CO_2 production test:

Hand shelled	6 replicates
Machine shelled	6 replicates
Undamaged machine shelled (no visible damage)	6 replicates
0% damage (uniform hand shelled)	3 replicates
25% damage	3 replicates
50% damage	3 replicates
75% damage	3 replicates
100% damage	3 replicates
Cleaned machine shelled	3 replicates
Uncleaned machine shelled	3 replicates
Completely undamaged machine shelled (internal cracks only)	3 replicates
Invisible external and internal damage	3 replicates
Empty jars as a check sample	3 replicates

A total of 48 different samples were hooked to the airflow and CO₂ lines in the air chamber. The experiment ran for about 400 h. Data recorded periodically for each sample included time in chamber, weight increase of CO₂, and the total g CO₂/kg dry matter of original sample.

O₂ Uptake Experiment

A series of experiments was conducted with a Gilson respirometer to measure the O₂ uptake of shelled corn. A differential respirometer described by Gilson (1963) was employed (Figure 13). In the Gilson respirometer, O₂ consumption of a sample was measured in a constant volume system. Small flasks were attached to a separate U-tube manometer as shown in Figure 15. A simple straight-through valve between the two arms of the manometer had two functions: (1) to provide a connection to and a free path between the two arms of manometer to equalize the pressure on the two columns of manometer fluid and (2) to connect the flask side of the manometer momentarily to the atmosphere for pressure equilibration. The flasks have space for a sample solution and small cylindrical reservoirs for an alkaline CO₂ absorbent. During the measurement, the manometer fluid in the closed manometer leg rises due to the O₂ consumption of the sample in the flask. A calibrated micrometer returns the manometer fluid to its balance position (original

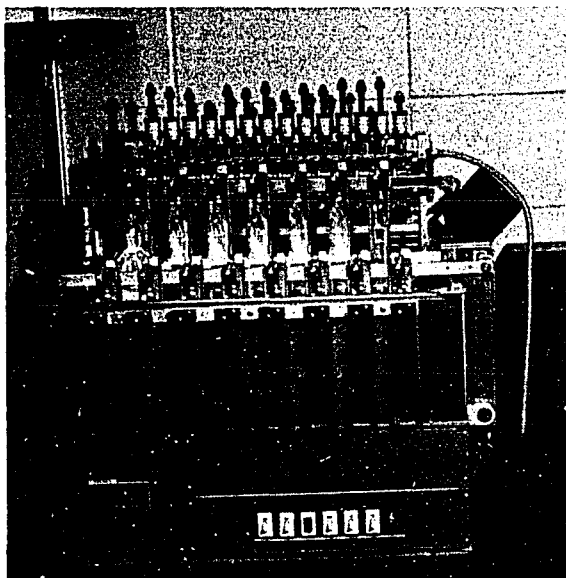


FIG. 13. GILSON DIFFERENTIAL RESPIROMETER

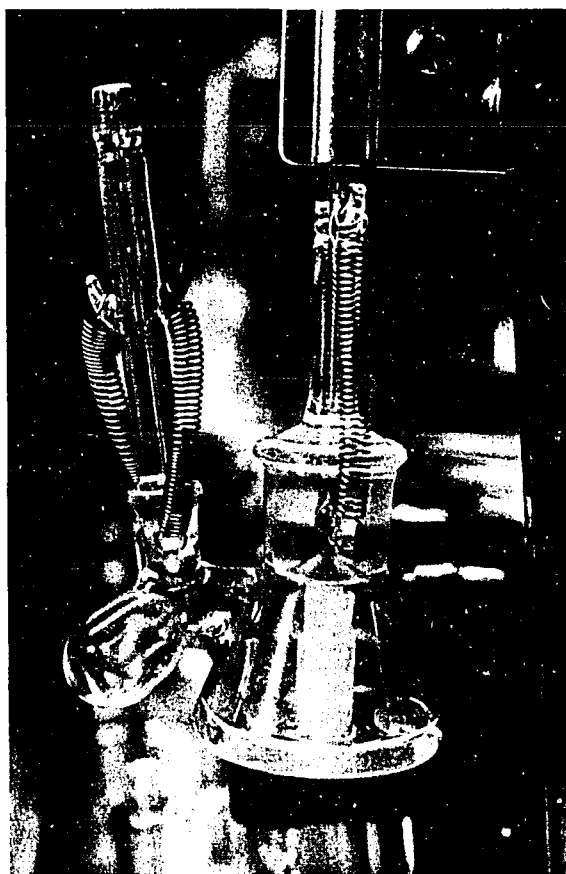


FIG. 14. GILSON DIFFERENTIAL RESPIROMETER FLASK

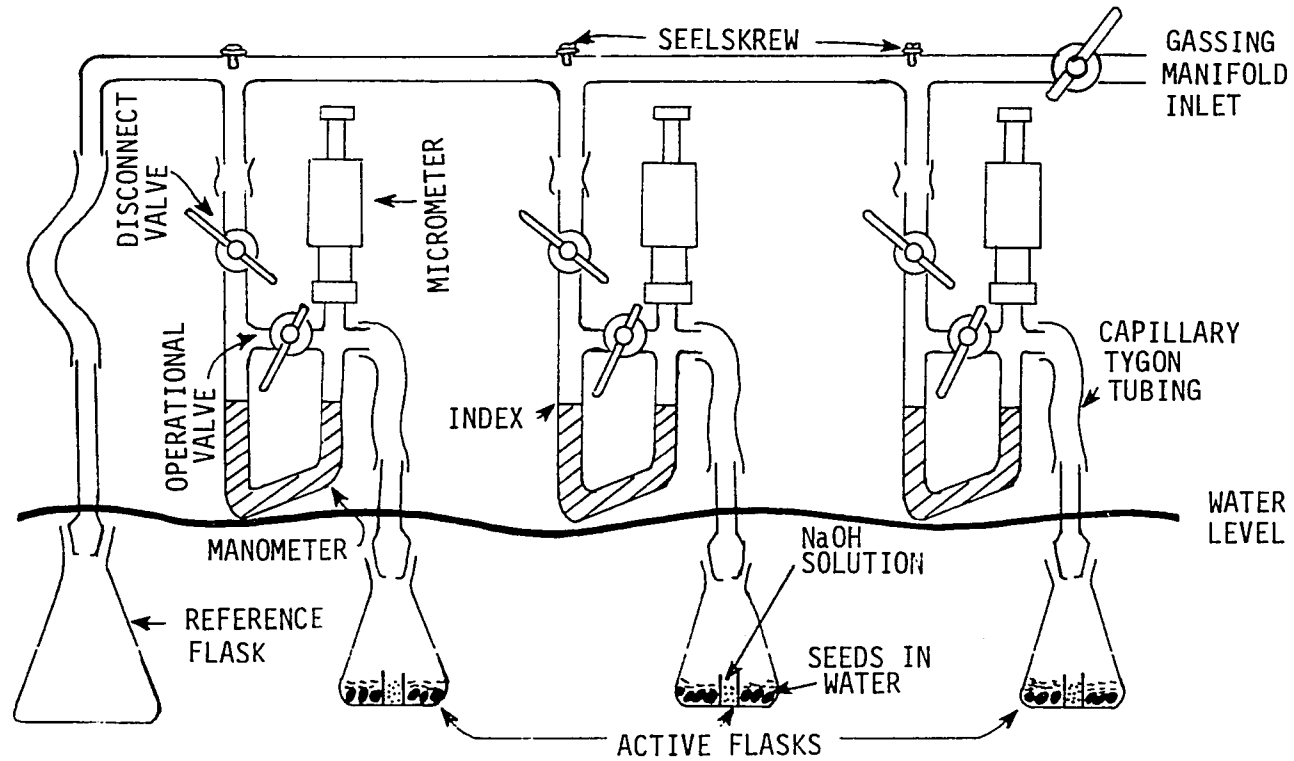


FIG. 15. DIFFERENTIAL RESPIROMETER SYSTEM WITH SINGLE REFERENCE FLASK
(GILSON, 1963)

level) by movement of piston in the enclosed volume.

To run the O_2 uptake experiment, 500-g samples of hand shelled, undamaged machine shelled (no visible damage), machine shelled, 0%, 25%, 50%, 75%, and 100% damaged kernels were prepared. Fourteen respirometer flasks were chosen each time for each sample. Each flask was prepared with 0.2- μ L NaOH solution (5N) in the center well, and a piece of 20 mm by 15 mm filter paper was folded at the same place to increase CO_2 absorbing capacity in the flask. Each flask was prepared with 10 weighed corn kernels and 10 μ L of de-ionized water to maintain high relative humidity (see Figure 14). The water bath of the respirometer was kept at 25°C. Barometric pressure within the lab was 734 to 747 mm of Hg. The flasks were attached to the manifold of the respirometer and immersed in the water. Vacuum grease was used at all joints to prevent gas leakage. The side arms of the flask were left open. The unused flasks were disconnected from the manifold. The system used about the same airflow rate as the CO_2 absorption train (1000 mL/min per 450 g or a little more than 2 mL/min per kg corn). In order to remove the traces of CO_2 and water vapor available in the air and eliminate any error which may effect our measurement, the air was passed through the packed mixture of dried magnesium perchlorate (for absorbing water) and active ascarite (for absorbing CO_2) in a tube. After 10 min, the

gassing valve was closed. Shaking of flasks in a water bath was stopped, and the sidearms were closed. The main disconnect was opened, and the flasks were shaken for 10 min, and the readings were started. The manometers were set to 100, and index lines were adjusted during equilibration (see Figure 15). Oxygen uptake was recorded every 10 min. Accurate temperature control in the stainless-steel water bath was provided by an electronic relay actuated by a hermetically sealed thermoregulator, easily set to a desired temperature by rotating an external magnet. Accuracy of control was $\pm 0.02^{\circ}\text{C}$. The readings were taken up to the time that no reading was possible (micrometer readings limitation). After 90 min, the system was stopped, and the flasks were disconnected. The contents of each flask were dried in a drying oven at 100°C for 24 h, and the dry weight was measured. The test of respiration was done for all the different damaged samples.

Water Uptake Experiment

In the fall of 1976, the effect of external and internal damage on water uptake of shelled corn was measured. Three samples (hand shelled corn, undamaged with no visible damage, and the damaged portion of machine shelled corn) of 100 g each with initial moisture content of 23% (wet basis) were prepared. These samples were held in rolled-towel germination

apparatus. Each roll consisted of 3 paper towels (0.36 x 0.61 m), two below the seed and one covering the seed. The seeds were arranged in one layer and moistened with enough distilled water to maintain a high relative humidity. The towels were loosely folded and placed in a plastic container covered with plastic bags to prevent evaporation. The samples were held in darkness at 25°F for 48 h. At 2 h intervals, the wet samples were blotted for 30 sec to remove any surface water on the seed coat. Immediately afterward, the total water gain was measured and recorded for each sample by using a Metler balance. After each measurement, the seeds, again arranged in one layer, were moistened with water. The towel was folded and held in the same condition as described previously.

To determine the possible differences between the undamaged portion of machine shelled (no visible damage) and hand shelled corn, the same experiment was repeated by using the following samples: hand shelled corn, undamaged machine shelled (internal cracks only), and invisible external and internal damage all with 25% MCWB. The experiment continued this time for 52 h, and the water uptake was measured as before.

RESULTS AND DISCUSSION

Damage and Moisture Content

Figure 16 and Table 4 show the various damage types and their distribution in three random samples of the machine shelled corn from the CO₂ production experiment. Chowdhury and Buchele (1976a) categorized the total damage percentage of machine shelled corn into four different types of damage, minor damage, major damage, severe damage, and fine materials. They defined minor damage as hairline cracks and spots of missing pericarp; major damage, as open cracks, chipped, and serious pericarp damage; severe damage, as kernels that had been broken, chipped, or crushed (more than 1/3 of the whole kernel missing); and fine material, as broken corn and foreign material passing through a 4.76-mm (12/64 in.) standard round-hole sieve. Broken corn and foreign material must not total more than 3% for corn to receive the USDA Official Grade No. 2 rating. This is well below the actual visible damage of 16.5%. Major and minor damage are not considered in broken corn and foreign material. As will be shown later, the official grades may not be useful in evaluating grain performance during storage.

Moisture content, determined by using the oven method for the different samples of field shelled and hand shelled agreed closely and averaged 25.5%.

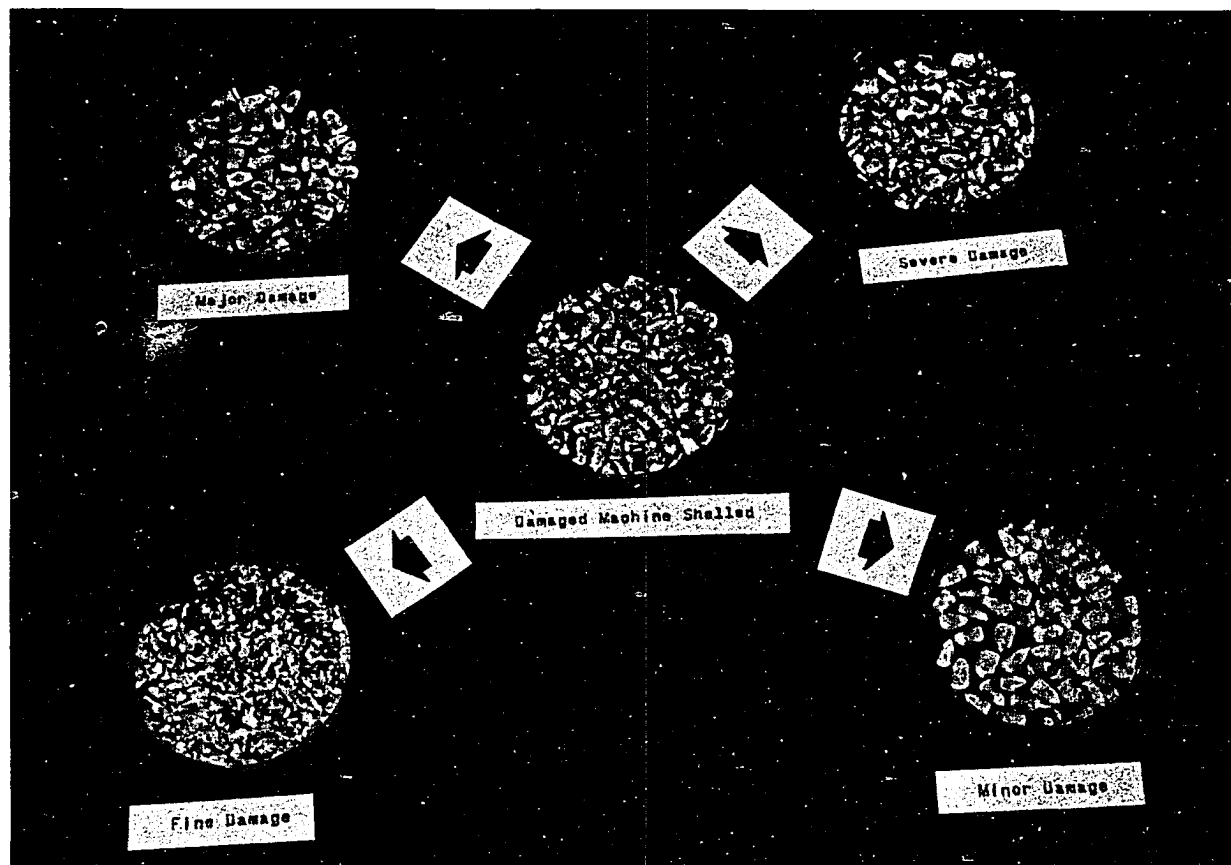


FIG. 16. CLASSIFICATION OF MACHINE SHELLED CORN INTO LEVELS OF MAJOR, SEVERE, MINOR AND FINE DAMAGE USING CHOWDHURY AND BUCHELE'S METHOD

Table 4. Four different types of damage in the machine shelled corn

Damage Level	Sample I	Sample II	Sample III	Average
Minor %	11	10.9	5.7	9.2
Major %	4.2	2.8	3.1	3.4
Severe %	1.6	3.9	3.8	3.1
Fine %	<u>0.2</u>	<u>1.4</u>	<u>0.8</u>	<u>0.8</u>
TOTAL %	17.0	19.0	13.4	16.5
Foreign material	0.3	0.4	0.3	0.3
Undamaged %	82.7	80.6	86.3	83.2

CO₂ Production

The test of CO₂ production by hand shelled corn was run for 300 h, at which time more than 7.35 g CO₂ was produced per kg of dry matter. Most of the samples were taken from the air chamber after 235 h, but some were left for more than 400 h (for more information see Appendix A on CO₂ production data). Visual observation showed that most samples had no mold spots. The corn had a good natural color. Some corn kernels had mold deterioration and a few germination sprouts. Figures 17 and 18 show the jars of various samples of shelled corn before and after CO₂ experiments. As Figure 18 indicates, the visual observation was



FIG. 17. JARS OF CORN SAMPLES BEFORE CO₂ EXPERIMENT



FIG. 18. JARS OF CORN SAMPLES AFTER CO₂ EXPERIMENT FOR VISUAL OBSERVATION

done to see the magnitude of spoilage due to the mold activity in the grain jars. The average portions of deteriorated grain in the jars was 0%, 12%, 23%, 50%, and 60% for 0%, 25%, 50%, 75%, and 100% damage, respectively. Although these portions are approximations, they indicate that the extent of deterioration is related to the damage level in the samples. Also, the color difference between samples was obvious. Figure 19 shows clearly the effect of damage level on the color of samples after storing grain for 400 h at the conditions favorable to deterioration. As the damage level increased from 0% to 100%, the golden color of corn changed to almost black. Figure 20 again illustrates very clearly the color difference of hand shelled corn, damaged kernels of machine shelled corn and machine shelled corn with no visible damage. The damaged corn sample had noticeable dark kernels, while some of the kernels had faded color. Machine shelled kernels with no visible damage had a better color than damaged kernels but still had more kernels with dark color.

Figure 21 shows the relationship between CO_2 production and time for hand shelled, undamaged portion of machine shelled, and machine shelled corn. Hand shelled corn with no visible and invisible damage (0% damage) had the lowest rate of CO_2 production, and the CO_2 production results with time fit a linear relationship. The undamaged portion of

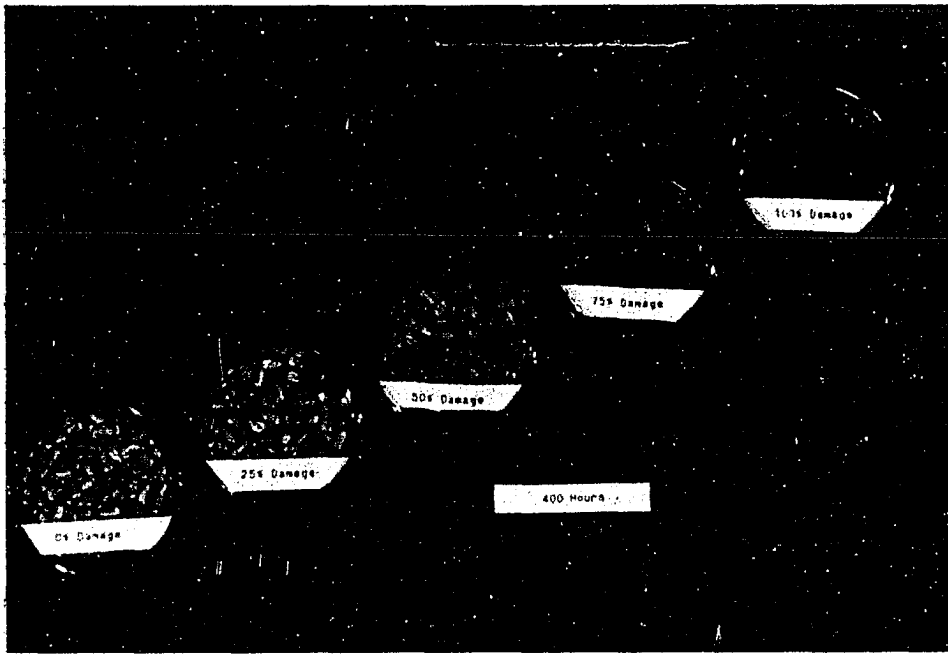


FIG. 19. COLOR DIFFERENCES OF PREPARED SAMPLES (GOLDEN TO ALMOST BLACK) DUE TO VARIOUS LEVELS OF (LEFT TO RIGHT) 0 TO 100% DAMAGE

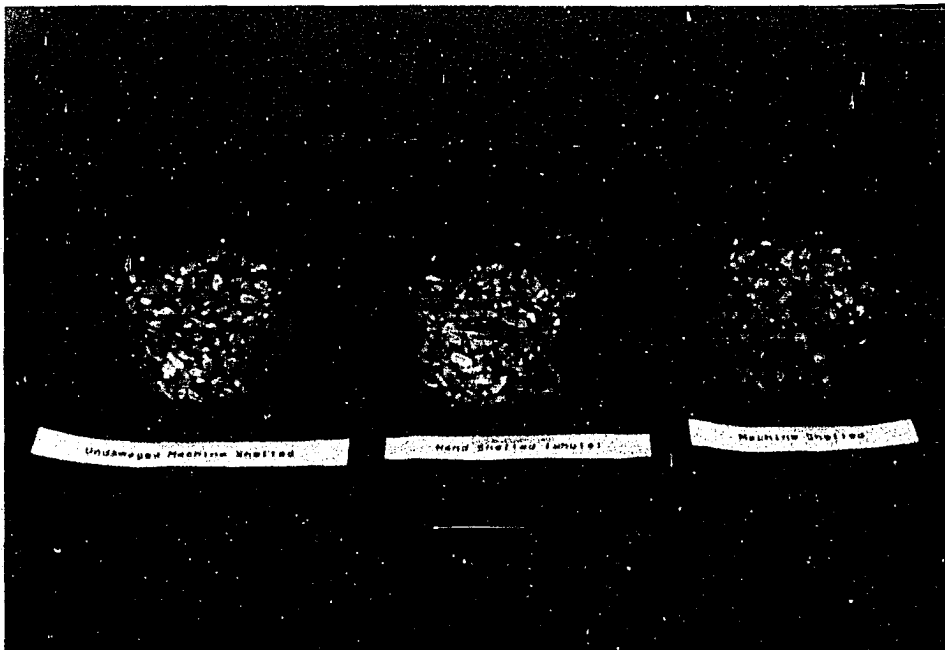


FIG. 20. COLOR DIFFERENCES OF (RIGHT TO LEFT) UNDAMAGED MACHINE SHELLING, WHOLE HAND SHELLING AND MACHINE SHELLING CORN

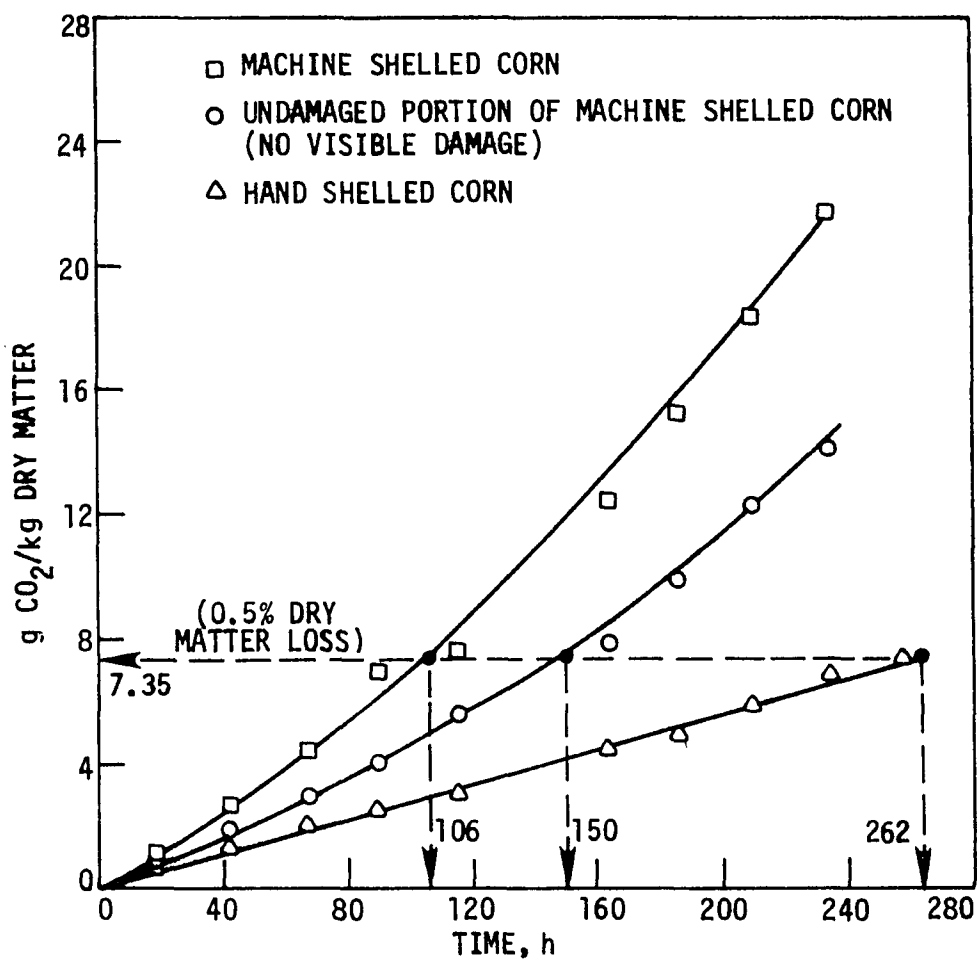


FIG. 21. CO₂ PRODUCTION OF SHELLLED CORN AT 25 °C AND INITIAL MCWB OF 25.5%

machine shelled corn, with some invisible cracks, showed a nonlinear relationship for CO_2 production versus time, with a higher slope than did hand shelled corn. Machine shelled corn, with visible and invisible damage showed again a nonlinear relationship between CO_2 production and time with a higher slope than that of undamaged machine shelled corn with no visible damage. Magnitude and severity of damage changed the constant rate of CO_2 production with time for hand shelled corn toward an increasing CO_2 production rate for machine shelled corn. Figure 22 shows CO_2 production with time for the prepared samples with various damage levels. The same trend of CO_2 production occurred as the damage level increased from 0% to 100%. There was a noticeable change from a linear to an exponential relationship as the damage level increased.

According to Saul (1967), the amount of deterioration that can be tolerated before market grade is affected is the loss of 0.5% dry matter or the production of about 7.4 g CO_2 per kg of original dry matter. The dashed lines in Figure 21 indicate this allowable storage time for the samples of hand shelled, undamaged portion of machine shelled (no visible damage), and machine shelled corn. Figure 22 shows the same thing for various levels of damaged corn mixed with uniform hand shelled corn and indicates that there is

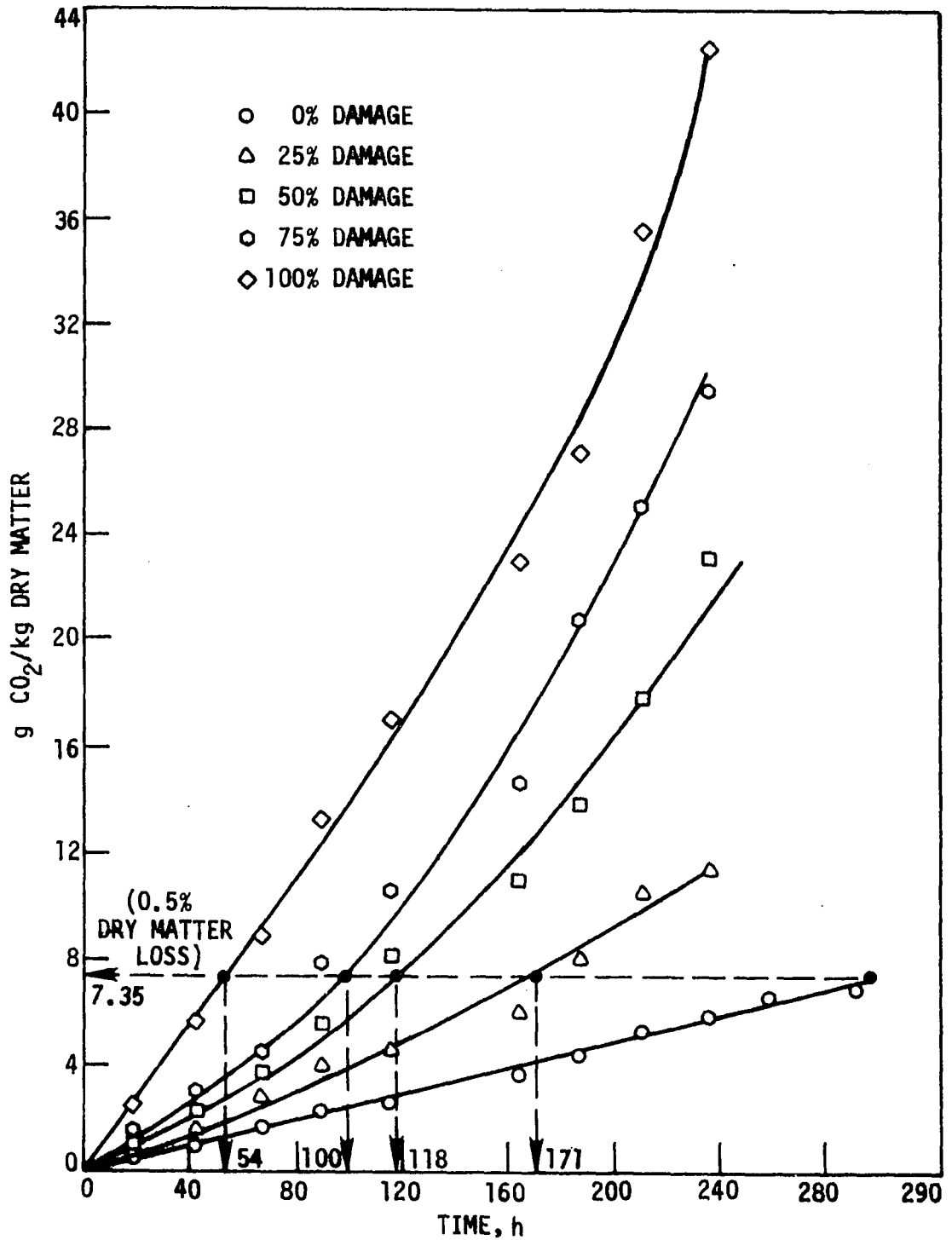


FIG. 22. CO₂ PRODUCTION OF SHELLED CORN AT 25°C AND 25.5% MCWB

a good trend (an exponential relationship) between the damage level of prepared samples and permissible storage time of shelled corn. Furthermore with available data, it would be possible to predict an experimental equation for allowable storage time of prepared samples to consume half a percent dry matter at the specified conditions of temperature and original moisture content of corn (25°C and 25% wet basis, respectively) in the following manner:

$$T = Ae^{-BD}$$

where

T = allowable storage time for 0.5% dry matter loss of prepared sample (various levels of damaged machine shelled mixed with uniform hand shelled corn) in h

A = constant coefficient

B = constant coefficient

D = total damage level in decimal point

After substitution of data, the following equation was obtained:

$$T = 286 e^{-1.70 D}$$

Table 5 shows the degree of conformity between calculated data from the empirical equation and actual data obtained from the experiment. It should be mentioned that this equation is valid for only prepared samples and not for shelled corn harvested by a conventional combine.

Table 5. Comparison of calculated time and actual time for allowable storage time of prepared samples to produce 7.4 g CO₂/kg dry matter

Damage level	Calculated time using empirical equation, h	Actual time obtained by experiment, h
5%	286	285
25%	187	171
50%	122	118
75%	80	100
100%	54	52

The CO₂ production vs. damage level in shelled corn after 235 h at 25°C and 25.5% MCWB are shown in Figure 23 and Table 6. The relationship between CO₂ production and damage level is approximately linear. Machine shelled and hand shelled corn had 21.66 g CO₂/kg dry matter and 6.70 g CO₂/kg dry matter, respectively. At the same time and conditions, undamaged machine shelled corn had about 14.06 g CO₂/kg dry matter. In other words, machine shelled corn with visible and invisible damage had more than 3 times ($\frac{21.66}{6.70} = 3.23$), and the undamaged machine shelled corn with invisible damage had more than 2 times, the ($\frac{14.06}{6.70} = 2.1$) deterioration rate of hand shelled corn.

The tests conducted on uniform kernels from the mid-section of the ear (0% damage) and hand shelled corn, which was the combination of uniform, round, and small kernels, are

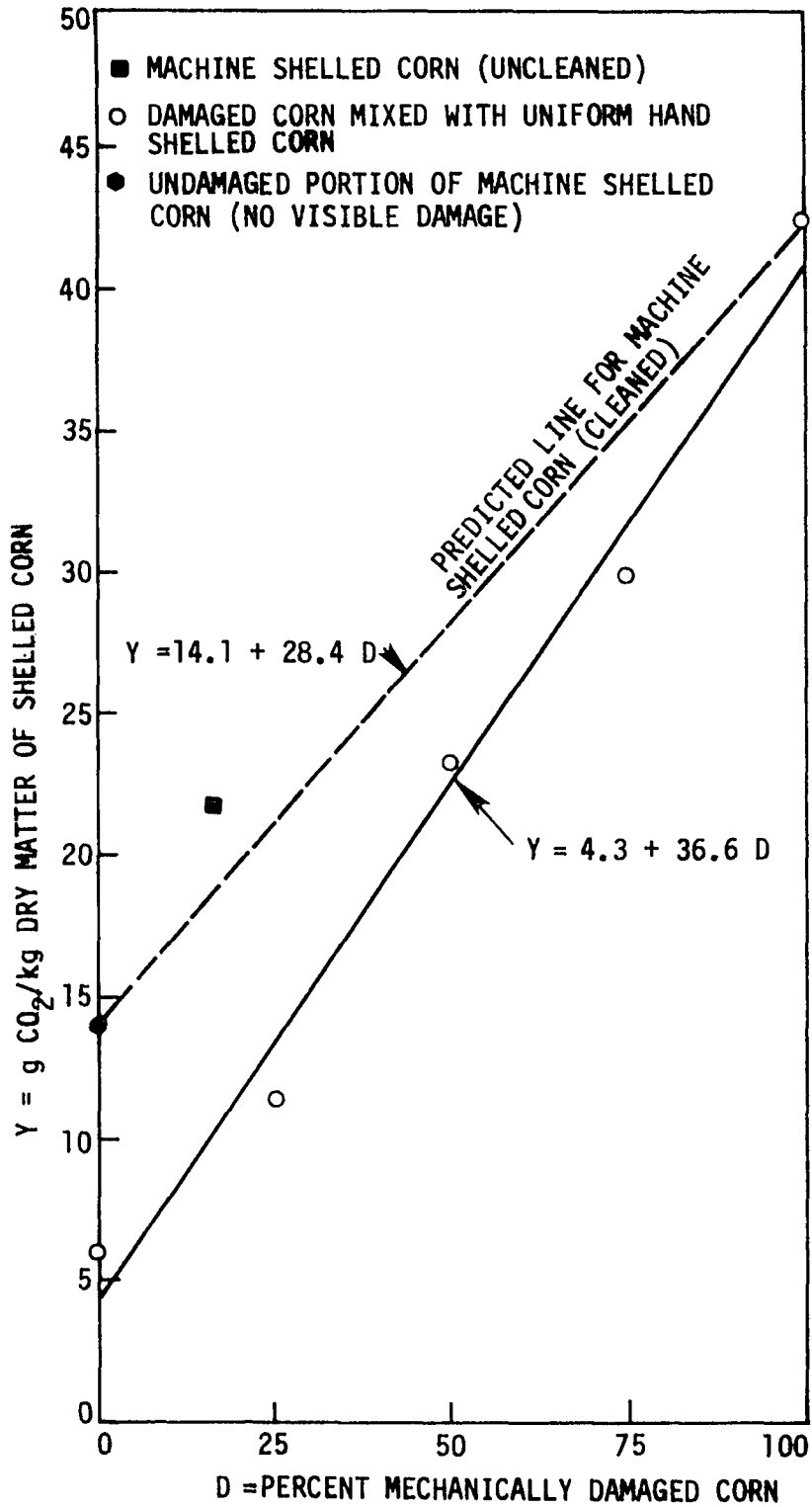


FIG. 23. CO₂ PRODUCTION AFTER 235 H WITH VARIOUS DAMAGE LEVELS OF SHELLED CORN AT 25°C AND INITIAL MCWB OF 25.5%

of considerable interest. Hand shelled corn did not respire in the same way as uniform kernels. The uniform kernels seemed to respire somewhat less per unit of dry weight than did the hand shelled kernels ($5.94 \frac{\text{g CO}_2}{\text{kg dry matter}}$ vs. $6.70 \frac{\text{g CO}_2}{\text{kg dry matter}}$). This suggests that embryo tissue is a larger percentage of the total dry weight in round and small kernels.

The amount of CO_2 production for three points of machine shelled corn is shown in Figure 23 (undamaged machine shelled = 0% damage, machine shelled = 16.5% damage, and damaged portion of machine shelled = 100% damage). The increase in CO_2 production versus damage level for shelled corn harvested by combine is shown by the equation:

$$Y = 14.1 + 28.4 D$$

where

D = total visible damage (wt. %)

Y = g CO_2 /kg dry matter after 235 h at 25°C and original 25% MCWB

Substituting into this equation, the predicted CO_2 production for machine shelled corn with about 16.5% of visible damage after 235 h would be $18.79 \text{ g CO}_2/\text{kg dry matter}$. The difference of this number from 21.66 for machine shelled (Table 6) owes to the fact that machine shelled corn was not cleaned before testing. Uncleaned machine shelled had about

Table 6. Total CO₂ production, g/kg dry matter of different corn samples with 25.5% MCWB at 25°C after 235 h

Replicates	Hand shelled	Machine shelled	Undamaged machine shelled	0% damage	25% damage	50% damage	75% damage	100% damage
1	9.36	27.51	15.70	7.25	14.27	30.07	43.50	41.60
2	4.12	25.78	13.23	2.89	17.21	8.00	31.24	43.55
3	7.34	21.09	5.37	7.67	2.80	31.60	14.92	42.24
4	8.17	13.25	15.69					
5	7.54	25.85	16.68					
6	3.25	16.46	17.61					
Average	6.70	21.66	14.06	5.94	11.43	23.22	29.89	42.48

15% more CO₂ production than did machine shelled corn with no foreign material.

Figure 24 shows in a better form the effect of cleaning on rate of CO₂ production of shelled corn during storage. Eliminating the foreign and fine materials reduces the rate of deterioration considerably. At the same conditions of moisture content, temperature, and time, machine shelled corn with no foreign and fine materials had about 50% less CO₂ than uncleaned machine shelled corn (see Appendix A, Table A10).

Prediction of allowable storage time for machine shelled corn has been the interest of research workers since grain harvesters were introduced to the farmers. Steele (1967) suggested the following equation which can be used to compute the permissible storage times for aerated shelled corn at various moistures, temperatures and mechanical damage levels based upon specific dry matter loss:

$$T = T_R \times M_T \times M_M \times M_O$$

where

T = estimated allowable exposure time before specific level of dry matter loss has been consumed in h

T_R = the reference time which was determined by Steele (1967) for a certain level of CO₂ production

M_T = temperature multiplier which is the inverse of R_T (relative deterioration rate for temperature), it can be read for any desired temperature using Figure 25

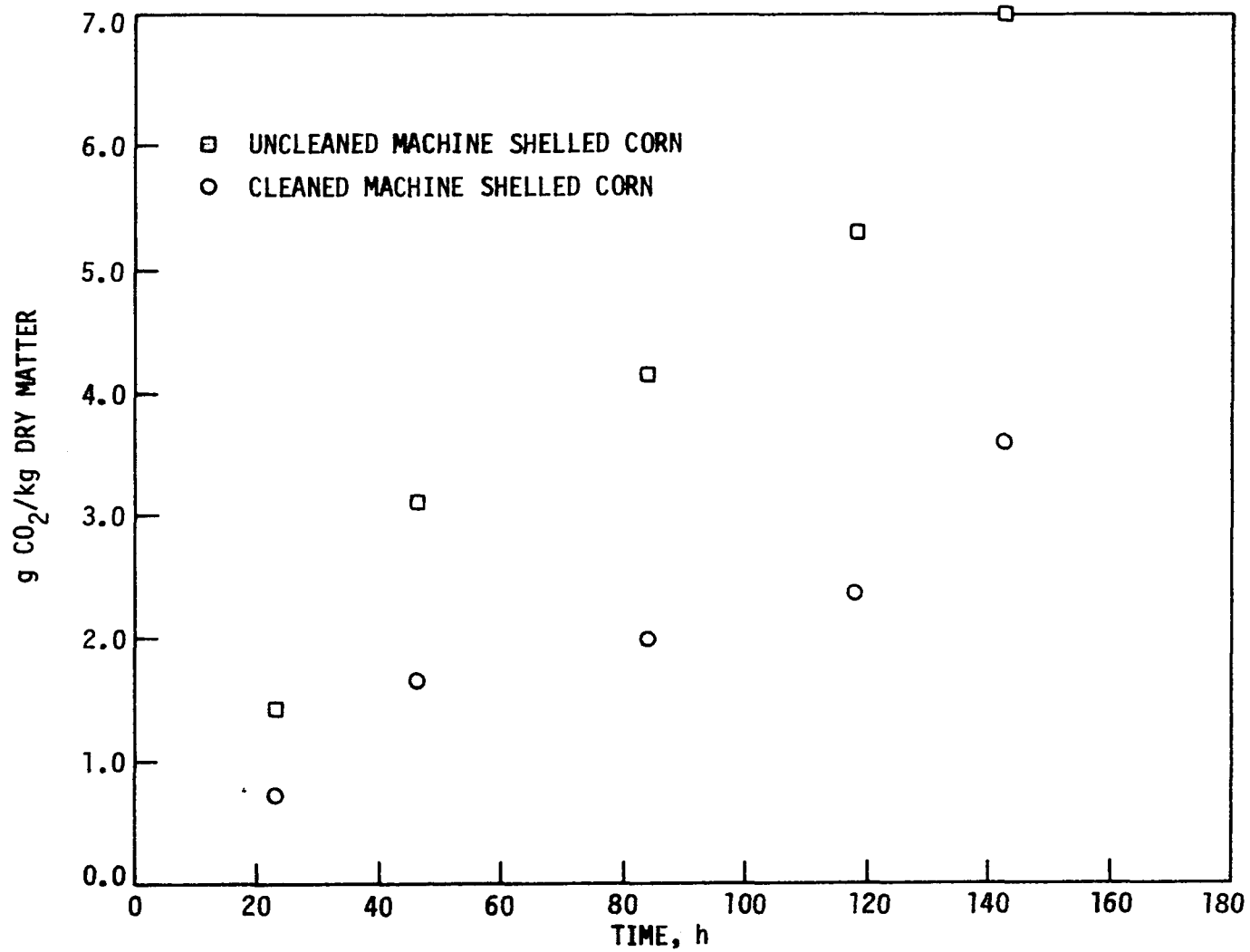


FIG. 24. EFFECT OF CLEANING ON CO₂ PRODUCTION OF MACHINE SHELLLED CORN WITH TIME AT 25°C AND INITIAL MCWB OF 25.5%

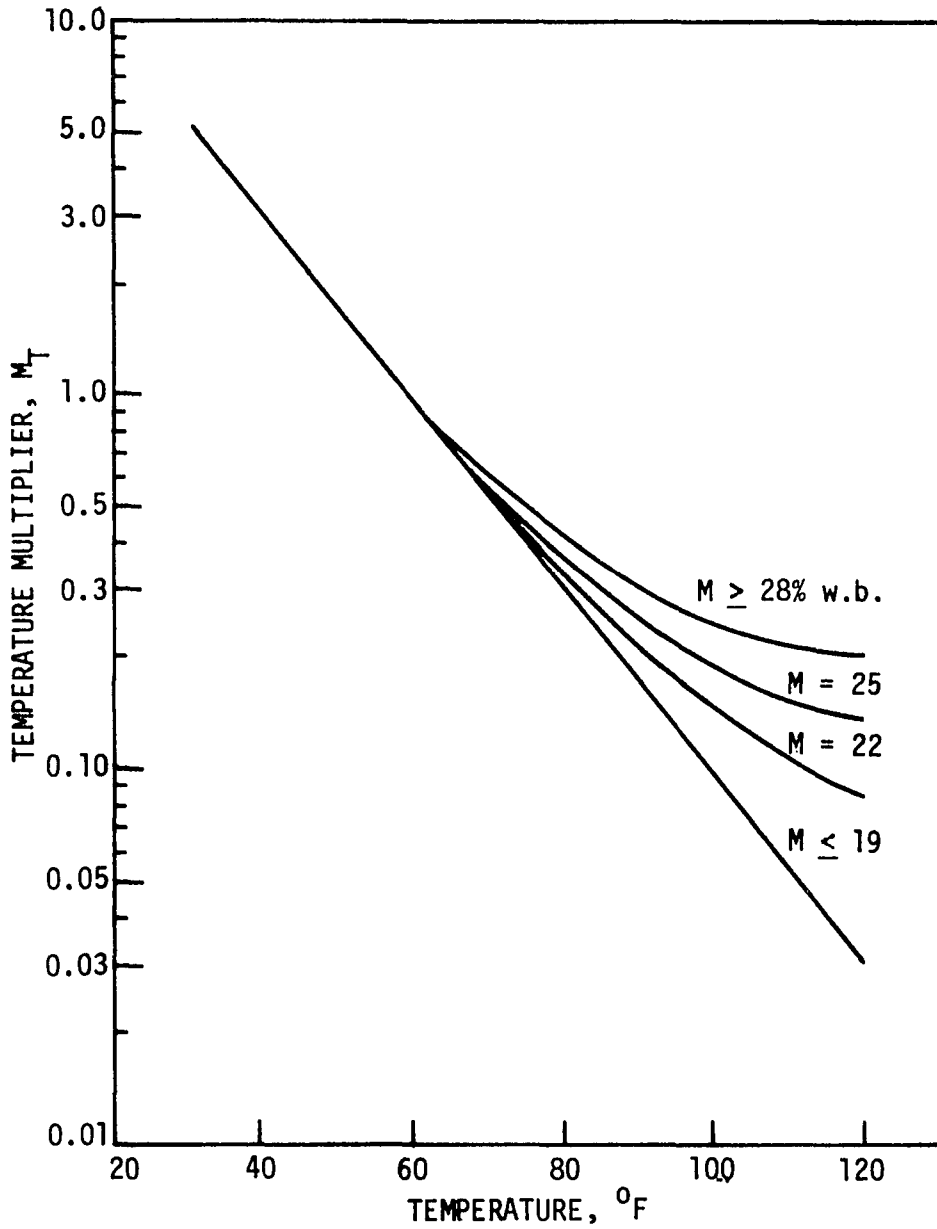


FIGURE 25. TEMPERATURE MULTIPLIER AS A FUNCTION OF TEMPERATURE (STEELE, 1967).

M_M = moisture multiplier (inverse of R_M , relative deterioration rate for moisture content), read for different moisture contents using Figure 26

M_D = mechanical damage multiplier which can be calculated in one of the three following empirical equations suggested by Steele (1967) based on dry matter loss:

$$\text{for } 0.1\% \text{ dry matter loss } M_D = 1.82 e^{-0.0143 D}$$

$$\text{for } 0.5\% \text{ dry matter loss } M_D = 2.08 e^{-0.0239 D}$$

$$\text{for } 1\% \text{ dry matter loss } M_D = 2.17 e^{-0.0254 D}$$

where

D is the percent of mechanical damage

For the reference time T_R , he suggested values of 58,230 and 356 hours for 0.1, 0.5 and 1% dry matter loss, respectively.

For instance, according to Steele's model, the allowable storage time of machine shelled corn with 16.5% damage, with initial moisture content of 25% wet basis and stored at 25°C to tolerate not more than 0.5% dry matter loss would be:

$$T = T_R \times M_T \times M_M \times M_D$$

$$T = 230 \times 0.40 \times 1.02 \times 1.40$$

$$T = 131 \text{ hours}$$

Results of this study showed that machine shelled corn stored 106 hours produced 7.4 g CO₂/kg for a loss of 0.5% dry matter. Considering the fact that machine shelled corn

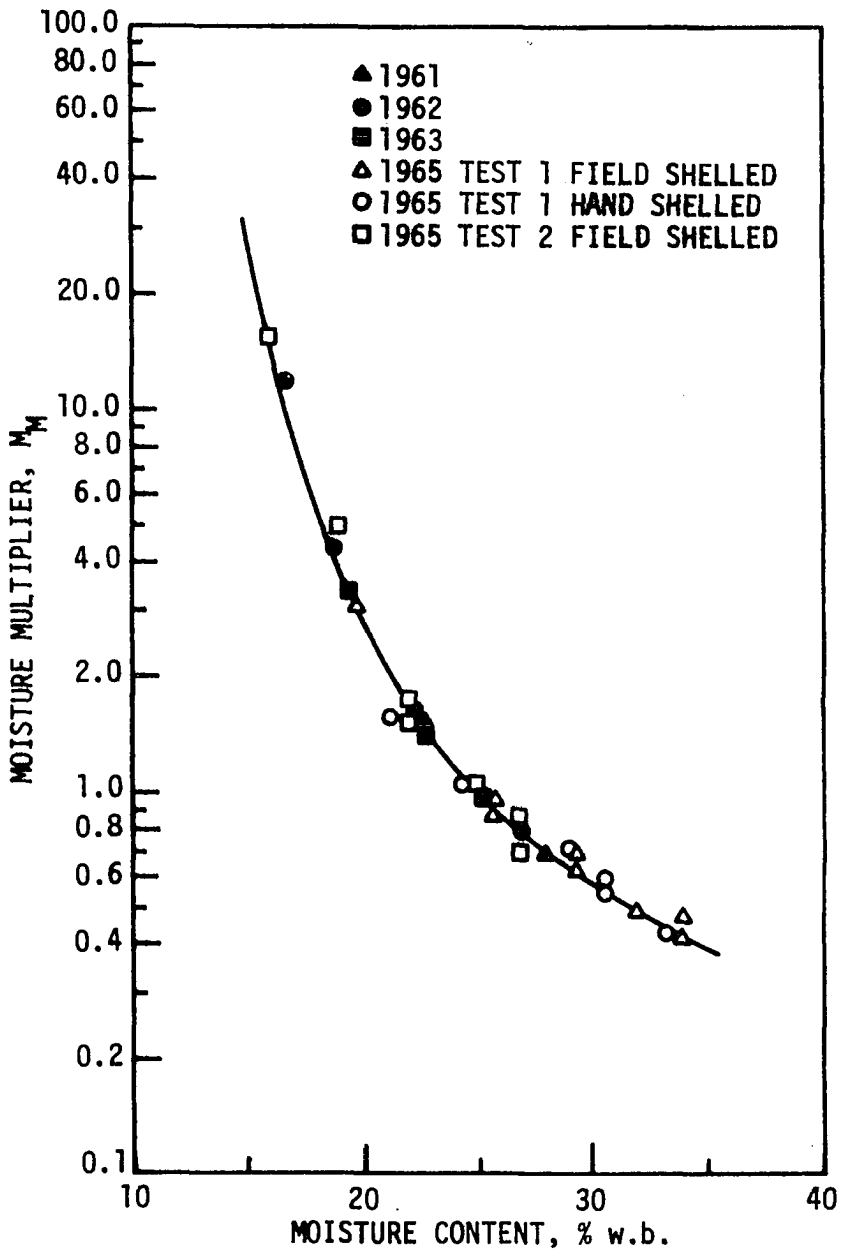


FIGURE 26. MOISTURE MULTIPLIER AS A FUNCTION OF INITIAL MOISTURE CONTENT (STEELE, 1967).

was not cleaned, it produced over 15% more g CO₂/kg dry matter than cleaned machine shelled corn. In other words the cleaned machine shelled corn needs more than 122 (106 + 106 x 15/100) hours to consume 0.5% dry matter. These results indicate that Steele's model and results of this study agree.

Although the visual inspection of each kernel of 25 kg of machine shelled corn to separate the visible damage portion from invisible damaged portion was a tedious and time-consuming operation, the unexpected results of deterioration rate of the undamaged portion of machine shelled corn (no visible damage) versus hand shelled corn persuaded us to divide this sample under a microscope into two groups consisting of invisible (external and internal) damage and undamaged machine shelled corn (internal cracks only) and then run a CO₂ production test.

The results of tests using two portions of machine shelled with no visible damage are shown in Figure 27. Statistical analysis was done for these data, and results are shown in Table 7. As a first conclusion, CO₂ production was a linear function of time:

for invisible external and internal damage
 $y = 2.85 - 0.081 t$

for undamaged machine shelled (internal cracks only)
 $y = 2.99 - 0.064 t$ where

y = carbon dioxide production, g CO₂/kg dry matter

t = time, h

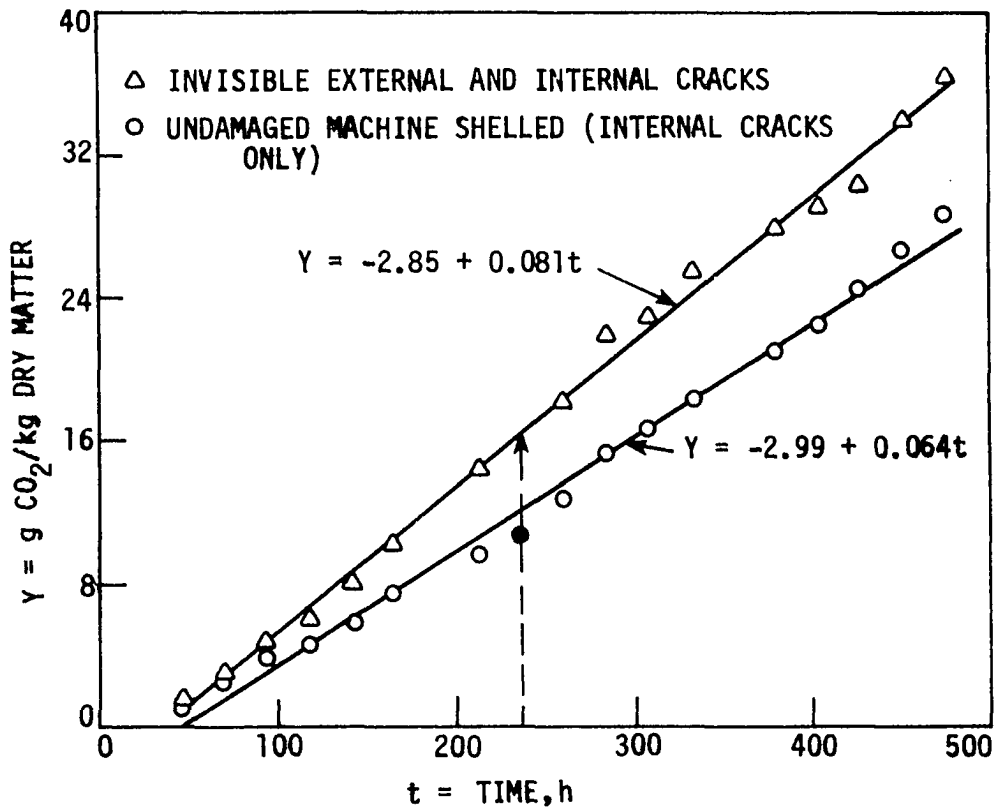


FIG. 27. EFFECT OF INVISIBLE DAMAGE OF MACHINE SHELLLED CORN ON CO₂ PRODUCTION

Table 7. Analysis of variance for CO₂ production of the two groups^a of undamaged machine shelled corn

Source	DF	Sum of squares	Mean squares
Model ^b	4	12089	3022.0
Error ^b	30	18	0.6
Model ^c	3	12043	4014.0
Error ^c	31	63	2.0

^aGroups of undamaged machine shelled (internal cracks only) and undamaged machine shelled (invisible external and internal cracks).

^bModel and its error for assumption of two intercepts and two slopes.

^cModel and its error for assumption of two intercepts and one slope.

$$F_{30}^1 = \frac{(63-18)/(31-30)}{0.6} = 75 \quad p^* > 10^{-4}$$

* Highly significant, hypothesis of having different slopes accepted.

The two intercepts were very close, but the two slopes of 0.081 and 0.064 were significantly different. There was a significant difference in the trend of CO₂ production or deterioration rate between the two portions of undamaged machine shelled corn. The following calculation shows the percentage of each in the undamaged portion of machine shelled corn for 1 kg undamaged machine shelled (no visible damage) which produced 14.06 g CO₂/kg dry matter (see Figure 27 and Table 6).

Because the undamaged machine shelled corn is a combination of corn with invisible external and internal cracks and corn with internal cracks, only the fractions of these components existing in the undamaged portion of the machine shelled corn can be estimated. Substituting into the equations of Figure 27 for $t = 235$ h, the CO_2 production for these fractions is 16.2 and 12.1 g, respectively. Thus, $0.48 (16.2) + 0.52 (12.1) = 14.06$.

We can thus conclude that the undamaged portion of the machine shelled corn is made up of 50% of corn with invisible external and internal cracks, and 50% of corn with only internal cracks. Weight measurement and calculation agreed and showed that about 30% of the undamaged kernels had internal cracks and 70% had invisible cracks (externally and internally).

Inasmuch as moisture content was the same for both samples, it shows that undamaged machine shelled corn is the combination of 30% shelled corn with internal cracks and 70% shelled corn with internal and tiny invisible pericarp damage.

O₂ Consumption

Grain deterioration is related to the respiration of the grain and of the accompanying microorganisms. Consumption of O₂ or production of CO₂ is a result of this respiration. Consumption of O₂, measured by respirometer, was investigated as a possible index of deterioration.

Figure 28 shows the relationship of O₂ uptake in μL per g dry matter with time. These results from Appendix B (data collected on O₂ uptake) indicate an almost linear relationship between O₂ consumption and time for different samples of machine shelled, undamaged machine shelled and hand shelled corn. There was some difference in rate of O₂ uptake among the samples. The difference was small because of a time limitation of about 2 h that the respirometer could work continuously.

A statistical analysis was performed for O₂ uptake of hand shelled, undamaged machine shelled (no visible damage), and machine shelled corn, and the following results were obtained:

1. There was a linear relationship between O₂ uptake and time: $y = 0.75 + 0.15 t$, $y = 0.83 + 0.18 t$ and $y = 0.52 + 0.21 t$ for hand shelled, undamaged portion of machine shelled, and machine shelled corn,

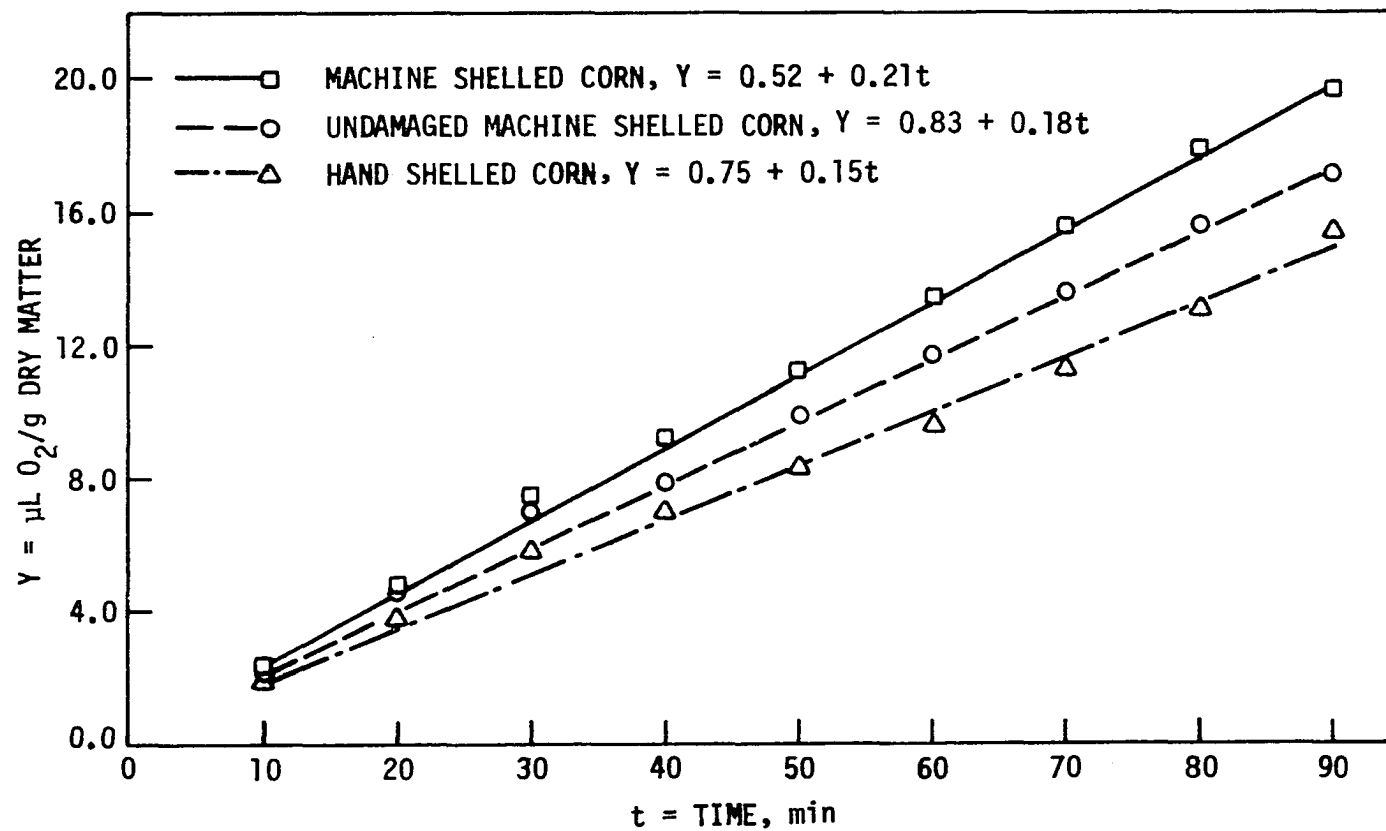


FIG. 28. OXYGEN UPTAKE OF SHELLLED CORN WITH TIME AT VARIOUS DAMAGE LEVELS

respectively. In the equation, $y = \mu\text{L O}_2/\text{g dry matter}$, and $t = \text{time, min.}$

2. There were significant differences between the slopes of each pair of regression lines (see Tables 8, 9 and 10). In other words, the trend of O_2 uptake for each sample was different.

Figure 29 shows that there was a direct relationship between O_2 uptake and time for various damage levels. Shelled corn with 100% damage had the highest rate of O_2 consumption, and corn with 0% damage had the lowest rate of O_2 uptake. The total O_2 uptake was converted to the total g CO_2 production/kg dry matter per h by using ideal gas law and the oxidation of glucose as a model.

The amount of oxygen consumption per unit dry weight and unit time was calculated from the following formula:

$$\mu\text{L oxygen uptake/min/g dry matter} = \frac{v \times \text{C.F.}}{t \times \text{D.M.}}$$

where

$v = \mu\text{L of O}_2 \text{ consumption}$

$\text{D.M.} = \text{dry matter weight in grain}$

$t = \text{duration of respiration in minute}$

$\text{C.F.} = \text{correction factor} = \frac{273 P_b}{(\theta + 273)(760)}$

where

$P_b = \text{barometric pressure of lab (mm Hg)}$

$\theta = \text{temperature of grain in respirometer}$

Since the P_b was between 734 to 744 mm Mercury and θ was

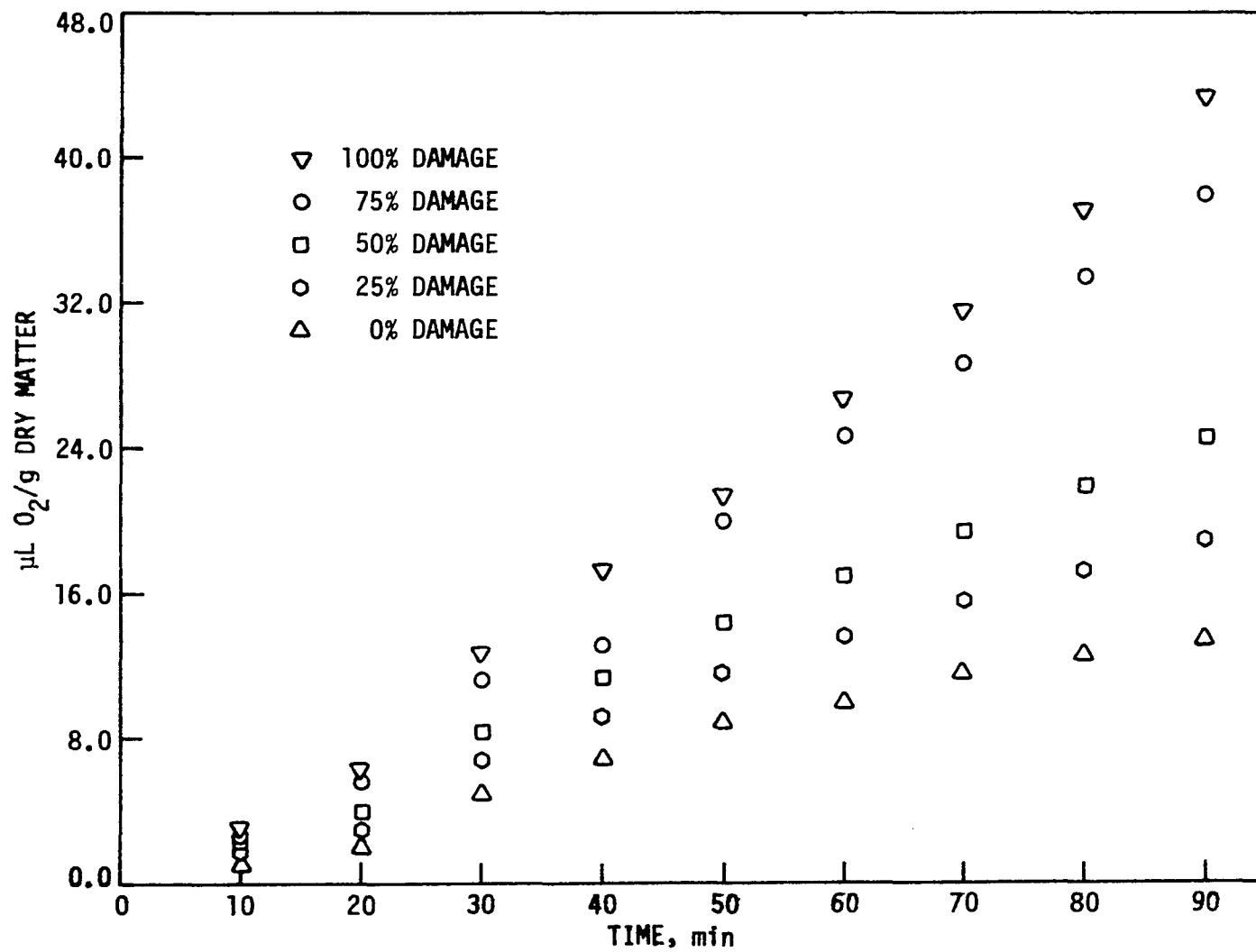


FIG. 29. OXYGEN UPTAKE OF SHELLLED CORN WITH TIME AT VARIOUS DAMAGE LEVELS

Table 8. Analysis of variance for oxygen uptake between hand shelled and machine shelled corn at 25°C and 25.5% MCWB after 90 minutes

Source	DF	SS	MS
<u>Full model</u> ^a			
Residual	14	1.02	0.07
<u>Reduced model</u> ^b			
Residual	15	13.00	0.87
F test = $\frac{(13.00 - 1.02)/(15-14)}{0.07} = 171 > 160^c$			

^aFull model = two intercepts and two slopes.

^bReduced model = two intercepts and one slope.

^cHighly significant (hypothesis of having different slopes was accepted).

Table 9. Analysis of variance for oxygen uptake between hand shelled and undamaged machine shelled corn at 25° and 25.5% MCWB after 90 minutes

Source	DF	SS	MS
<u>Full model</u> ^a			
Residual	14	1.30	0.09
<u>Reduced model</u> ^b			
Residual	15	4.01	0.03
F test = $\frac{(4.01 - 1.30)/(15-14)}{0.09} = 30.11 > 30^c$			

^aFull model = two intercepts and two slopes.

^bReduced model = two intercepts and one slope.

^cHighly significant (hypothesis of having different slopes was accepted).

Table 10. Analysis of variance for oxygen uptake between undamaged machine shelled and machine shelled corn at 25°C and 25.5% MCWB after 90 minutes

Source	DF	SS	MS
<u>Full model</u> ^a			
Residual	14	1.29	0.09
<u>Reduced model</u> ^b			
Residual	15	4.58	0.30
F test = $\frac{(4.58 - 1.29)/(15-14)}{0.09} = 36.5 > 35^c$			

^aFull model = two intercepts and two slopes.

^bReduced model = two intercepts and one slope.

^cHighly significant (hypothesis of having different slopes was accepted).

around 25°C to 27°C (77° to 81°F), correction factor didn't have that much effect on total oxygen uptake. In other words, the correction factor was around 0.85 to 0.95 (close to 1) and the oxygen uptake readings in respirometer didn't need that much correction.

$$\frac{P}{P_O} \frac{V}{V_O} = \frac{T}{T_O} \quad (\text{ideal gas law})$$

where

P = barometric pressure of lab (736 to 740 mm Hg)

P_O = atmospheric pressure = 760 mm Hg

T = 273 + θ, 298° to 300°K

T_O = 273 + 0 = 273°K

$$V_o = 22,400 \text{ cm}^3/\text{mole of gas}$$

V = volume of the gas at specified temperature and pressure

The factor $\frac{V}{V_o}$ determined the molecular ratio of O_2 and CO_2 at the specified conditions of the respiration experiment (oxidation of glucose) and the total g CO_2 /kg dry matter was calculated.

Table 11 shows the total oxygen uptake in μL per g of dry matter per min, equivalent g CO_2 per kg dry matter per h and the total g CO_2 per kg dry matter after 235 h. As the damage level increased from 0% to 100%, the equivalent of carbon dioxide production of respirometer changed from 4 to 33 g/kg. These equivalent CO_2 results from the respiration experiment were quite comparable with the total g CO_2 /kg dry matter obtained by CO_2 production system after 235 h. Figure 30 shows the relationship between the first group of results versus the second group of results. There was a very high correlation of $r = 0.94$ between the two groups of results. In other words, the results of the O_2 uptake experiment had a good conformity with CO_2 production results.

Water Uptake Results

Figure 31 shows the trend of water uptake for hand shelled, undamaged portion machine shelled, and damaged portion of machine shelled corn. Because the shelled corn was

Table 11. Comparison of CO₂ production and CO₂ equivalent of O₂ uptake

Sample	Hand shelled	Undamaged machine shelled	Machine shelled	0% D	25% D	50% D	75% D	100% D
O ₂ uptake								
$\frac{\mu\text{L O}_2}{\text{g dry matter min}}$	0.17	0.19	0.25	0.16	0.73	0.73	1.00	1.39
$\frac{\text{Equivalent g CO}_2}{\text{kg dry matter h}}$	0.017	0.020	0.026	0.016	0.076	0.088	0.104	0.144
Total equivalent CO ₂ production after 235 h								
$\frac{\text{g CO}_2}{\text{kg dry matter}}$	4.14	4.69	6.07	3.88	17.76	20.81	24.57	33.80
Total CO ₂ pro- duction after 235 h								
$\frac{\text{g CO}_2}{\text{kg dry matter}}$	6.70	14.06	21.66	5.94	11.43	23.22	29.89	42.48

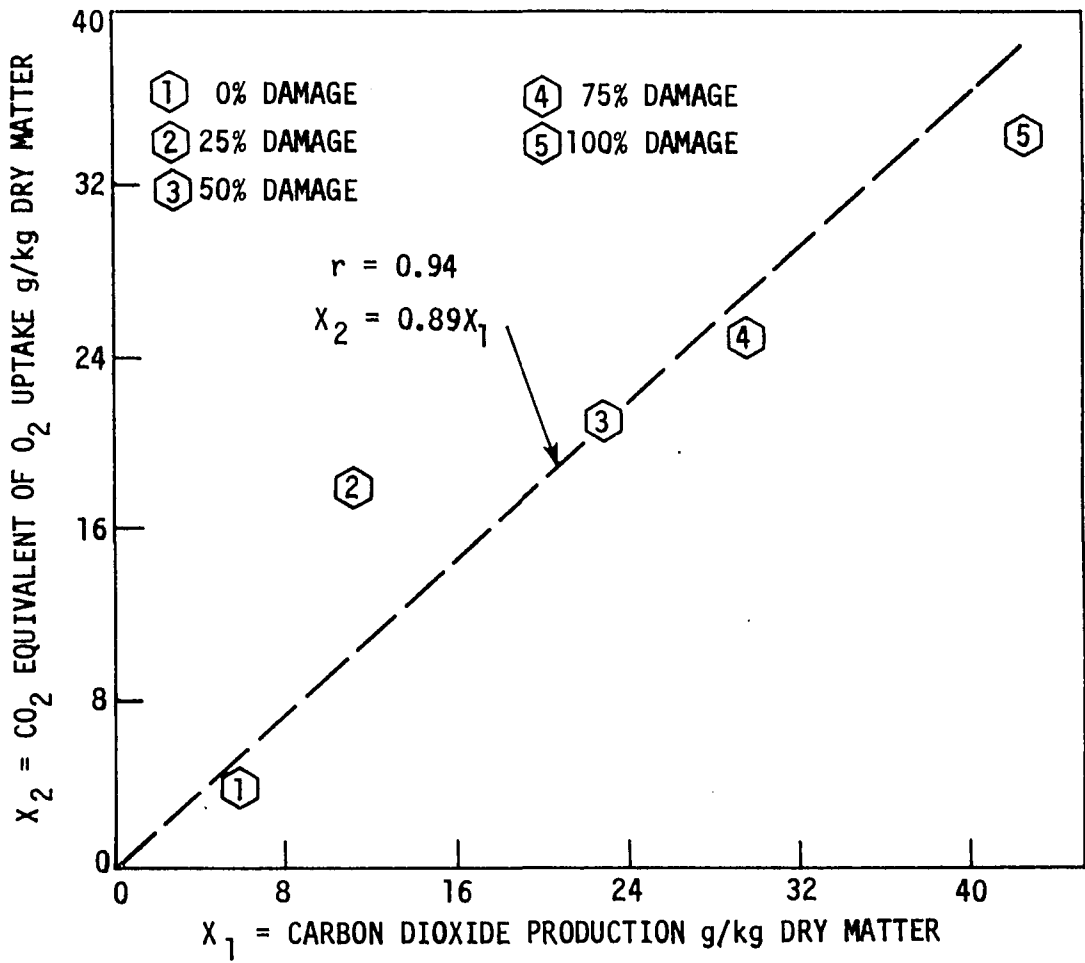


FIG. 30. CORRELATION OF CO_2 EQUIVALENT OF O_2 UPTAKE RESULTS AND CO_2 PRODUCTION RESULTS

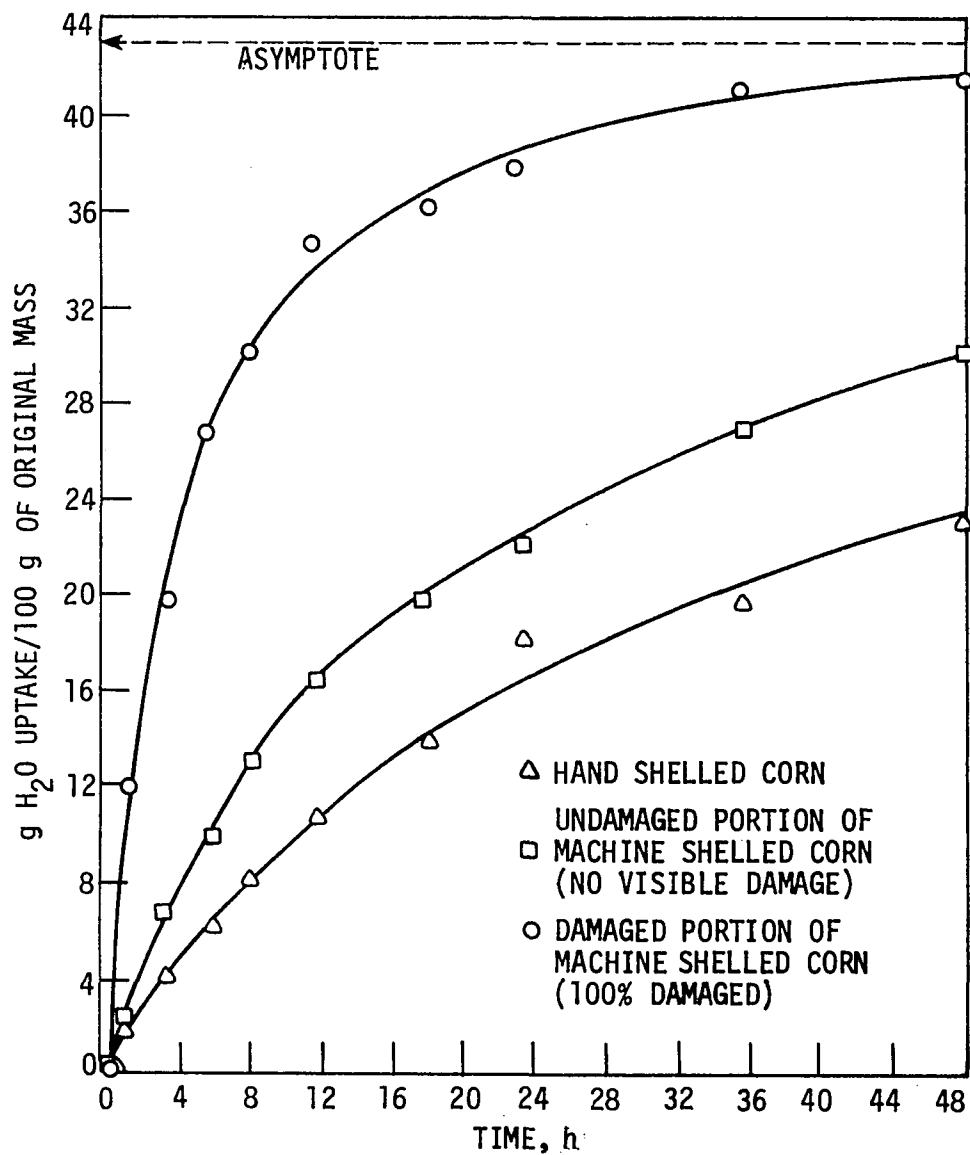


FIG. 31. RATE OF WATER UPTAKE FOR DIFFERENT SHELLLED CORN WITH TIME AT 25°C AND INITIAL MCWB OF 23%

exposed at almost 100% relative humidity, the quantity of water uptake of the seeds approached the value of the asymptote and merged with a curve, which is called an exponential phase of imbibition. The asymptote is the capacity of the seeds to absorb water and does not change with increasing time. In this study the three samples of hand shelled corn, undamaged portion of machine shelled corn (no visible damage), and damaged portion of machine shelled corn were reached to the asymptote of 43.0 g H₂O/100 g of original mass (see Figure 31).

Documented literature and the results of this experiment (see Appendix C) showed that even broken seed without a viable embryo (dead seeds) were capable of an exponential phase of imbibition. According to Blacklow (1972), a marked linear phase of imbibition (first part) was a characteristic of living seeds (whole, sound kernels). He defined the rate of water uptake, $\frac{dw}{dt}$ as being proportional to the difference between the water-absorbing capacity of the seeds, $f(t)$, and the water content, W , plus a constant rate of water uptake because of the change in water capacity of the seeds, b :

$$\frac{dw}{dt} = k[f(t) - w] + b$$

Consequently, k is a measure of permeability of the seeds to the water during the exponential phase, which is related to the breakage in seed coat; $f(t)$ is a measure of changing capacity of the seeds to imbibe water, which is dependent on the growth of embryo; and b is a measure of the

rate of imbibition during the linear phase.

As Figure 31 shows, both equilibrium moisture content and sorption rates differed distinctively between sound and damaged samples. In general, damaged corn had higher sorption rates and reached equilibrium sooner than did hand shelled corn. Equilibrium moisture contents, from high to low, were machine shelled corn, undamaged portion of machine shelled, and hand shelled corn. Differences in rate and equilibrium moisture content among the samples were attributed to the surface characteristics of kernels. According to Chung (1972), damaged kernels have higher specific conductance than does sound corn because the seed coat is broken and the endosperm is exposed. Consequently, the resistance to moisture movement is considerably reduced. Also, more adsorption sites are readily available in broken kernels than in whole sound kernels.

The equilibrium moisture content was a good indicator of a difference in physical quality of the first group of undamaged machine-shelled, which presumably had only internal cracks, versus the second group, which had invisible external and internal cracks, and for both compared with hand shelled corn. Figure 32 shows that the undamaged corn with invisible external and internal cracks had a greater quantity of water uptake than did corn with internal cracks only. The two groups both had a higher rate and greater quantity of water uptake than did hand shelled corn. Statistical analysis

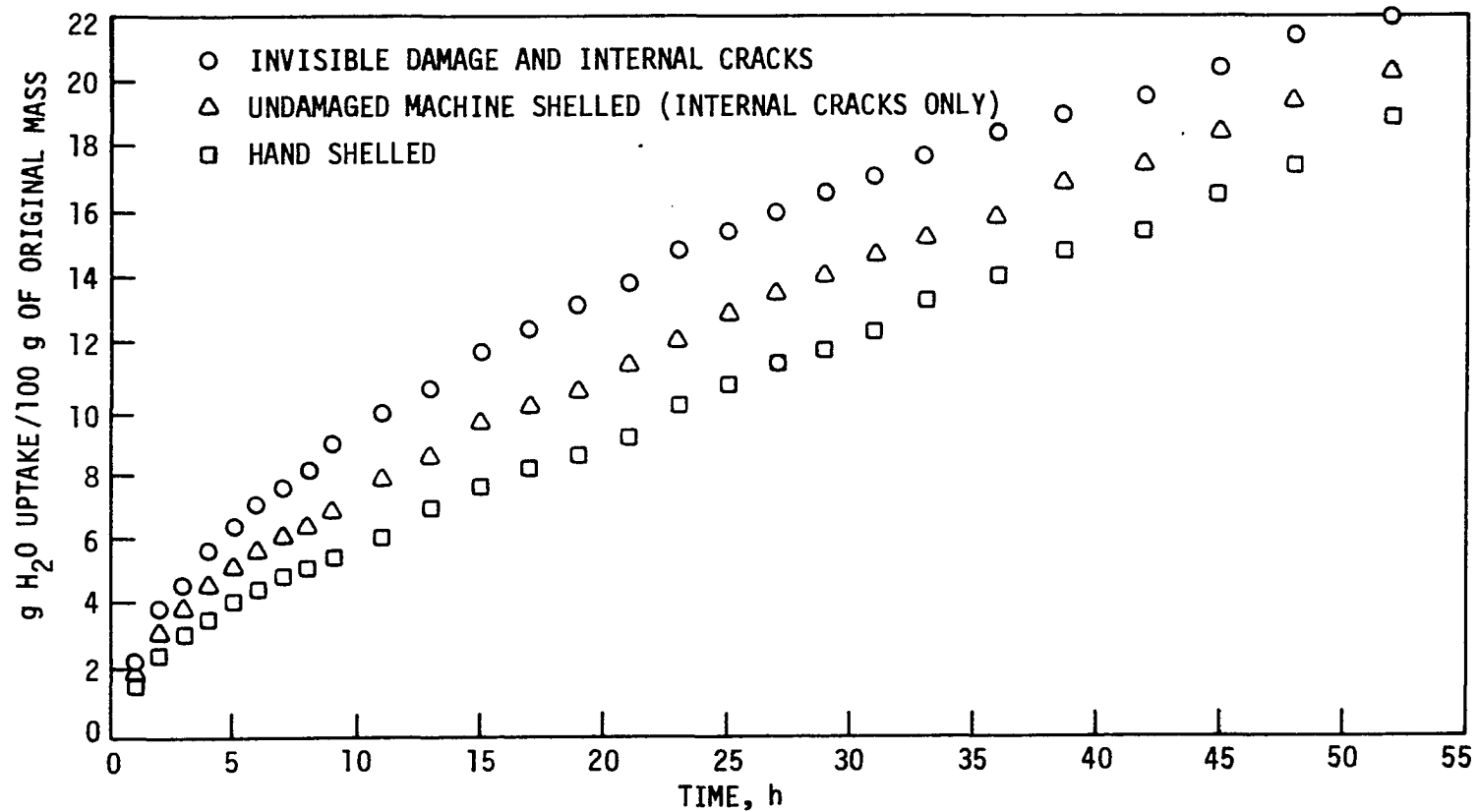


FIG. 32. EFFECT OF INVISIBLE DAMAGE OF MACHINE SHELLED CORN ON WATER UPTAKE WITH TIME AT 25°C AND INITIAL MCWB OF 25.5%

was performed for these data, and the following conclusions were made:

1. Water uptake was a quadratic function of the time that seed was in contact with water (see Figures 31 and 32):

$$W = a + bt - ct^2$$

2. The coefficients of a , b , and c were significantly different for hand shelled, undamaged machine shelled, and pericarp damaged corn (see Table 12).
3. There were significant differences between the initial slopes for the three plots and, therefore, a significant difference in the rate of water uptake between the three samples. It can be concluded that undamaged machine-shelled corn had some invisible or internal cracks that could absorb or hold more water than did hand shelled corn.

Table 12. Analysis of variance for water uptake of different samples of shelled corn at 25°C after 52 h

Source	DF	Anova SS	F Value	PR F
Hour	27	7685	538	0.001 ^b
Group ^a	2	508	480	0.001
Group-Hour	54	77	3	0.001

^aGroup = hand shelled, undamaged machine shelled (internal cracks only), and invisible (external and internal) damage.

^bHighly significant.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Deterioration of hand-shelled corn (no visible or invisible damage) over time fit a linear relationship.
2. As the internal and external damage increases from 0% damage (hand shelled corn) to 100% damage (damaged portion of machine shelled corn), CO_2 production with time changes from a constant rate to a variable (increasing) rate.
3. As the total visible damage increased from 0% to 100%, the total CO_2 production increased in a linear fashion.
4. Machine shelled corn (visible and invisible damage) and undamaged machine shelled corn (no visible damage) had 3 times and 2 times, respectively, the deterioration rate of hand shelled corn.
5. Undamaged machine shelled corn (no visible damage) was a combination of 30-50% shelled corn with internal cracks and 50-70% shelled corn with invisible cracks (external and internal).
6. Elimination of fines and foreign material from machine shelled corn reduces the rate of deterioration (CO_2 production) about 50%.
7. There was a linear relationship of O_2 uptake over time for hand shelled, machine shelled, and undamaged machine shelled corn. Machine shelled corn had a higher rate of

oxygen uptake than did undamaged machine shelled and hand shelled corn.

8. There was a good correlation between the results of O_2 uptake and CO_2 production for 0%, 25%, 50%, 75%, and 100% damaged corn. Oxygen uptake can be an indicator of damage level.

9. Water uptake of the seed was a quadratic function of the time that shelled corn was in contact with water.

10. Damaged portions of machine shelled corn (100% damage) had a greater rate of water uptake than did undamaged machine shelled corn and hand shelled corn.

SUGGESTIONS FOR FUTURE RESEARCHERS

Most of the losses different grain users have to tolerate are side effects of internal and external damage on shelled corn. Future researchers should redesign, construct and operate the shelling and handling machines in such a way as to shell and handle the corn at relatively high capacity with the least possible internal and external damage, while they try to maintain the investment and operation cost at a reasonable level.

Since there is a considerable difference in rate of deterioration of machine shelled corn before and after cleaning, and according to Saul and Steele (1966), it costs more to dry the damaged corn, it is necessary and appropriate to develop cleaning systems with high capacity, efficiency, and minimum cost. As a possible index for damage level in shelled corn more research is needed to measure O_2 uptake for different varieties of shelled corn, at different ranges of original moisture content and storage temperature.

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APPENDIX A: EXPERIMENTAL DATA CO_2 ABSORPTION IN ASCARITE
TUBES PLUS TOTAL CO_2 /kg DRY MATTER OF SHELLLED
CORN WITH INITIAL MOISTURE CONTENT OF 25.5%
DUE TO THE AERATION AND RESPIRATION AT 25°C

Table A1. Undamaged machine shelled corn with no external cracks (internal cracks only)

Test duration in hours	Replicate I			Replicate II			Replicate III			Average of three replicates total CO ₂ g/kg dry matter
	Tube #1	Tube #2	Total CO ₂ g/kg dry matter	Tube #1	Tube #2	Total CO ₂ g/kg dry matter	Tube #1	Tube #2	Total CO ₂ g/kg dry matter	
47.5	0.12	0.00	1.12	0.02	0.02	0.40	0.17	0.00	1.54	1.02
70.3	0.27	0.00	2.43	0.18	0.02	1.83	0.34	0.00	3.07	2.45
93.5	0.38	0.00	3.42	0.30	0.02	2.96	0.46	0.00	4.20	3.53
118.3	0.49	0.01	4.43	0.45	0.02	4.30	0.55	0.00	4.93	4.56
142.4	0.62	0.01	5.72	0.62	0.03	5.85	0.64	0.00	5.81	5.79
164.7	0.80	0.05	7.56	0.74	0.10	7.56	0.77	0.01	7.00	7.37
212.6	1.07	0.05	10.06	1.00	0.13	10.15	0.93	0.01	8.50	9.57
237.0	1.23	0.06	11.58	1.11	0.18	11.59	0.97	0.02	8.90	10.69
260.8	1.36	0.19	13.95	1.18	0.35	13.71	1.10	0.09	10.67	12.78
284.9	1.51	0.31	16.40	1.35	0.55	17.08	1.18	0.22	12.58	15.36
308.9	1.65	0.46	18.87	1.36	0.69	18.36	1.22	0.23	12.98	16.74
333.7	1.80	0.50	20.62	1.45	0.80	20.17	1.26	0.27	13.69	18.16
380.2	2.08	0.61	24.11	1.67	0.93	23.37	1.32	0.36	15.12	20.86
405.5	2.18	0.76	26.39	1.79	1.05	25.53	1.35	0.37	15.41	22.44
428.1	2.27	0.93	28.71	1.91	1.24	28.26	1.37	0.49	16.68	24.55

452.8	2.37	1.13	31.37	2.01	1.41	30.73	1.40	0.62	18.03	26.71
475.8	2.48	1.28	33.75	2.12	1.55	32.92	1.41	0.76	19.46	28.71

Table A2. Undamaged machine shelled corn with invisible external cracks

Test duration in hours	Replicate I			Replicate II			Replicate III			Average of three replicates total CO ₂ g/kg dry matter
	Tube #1	Tube #2	Total CO ₂ g/kg dry matter	Tube #1	Tube #2	Total CO ₂ g/kg dry matter	Tube #1	Tube #2	Total CO ₂ g/kg dry matter	
47.9	0.25	0.00	2.26	0.15	0.00	1.32	0.02	0.02	0.33	1.31
70.0	0.48	0.00	4.27	0.34	0.00	3.11	0.19	0.02	1.85	3.08
93.2	0.76	0.00	6.83	0.54	0.01	4.95	0.27	0.02	8.65	4.81
117.9	0.86	0.01	7.76	0.73	0.01	6.63	0.35	0.02	3.33	5.90
142.2	1.23	0.01	11.17	0.95	0.01	8.66	0.46	0.03	4.40	8.08
164.8	1.46	0.07	13.78	1.16	0.07	11.04	0.70	0.03	6.59	10.47
213.0	2.13	0.17	20.64	1.53	0.09	14.51	0.87	0.03	8.12	14.42
236.9	2.27	0.22	23.33	1.56	0.11	15.02	0.88	0.04	8.21	15.52
261.2	2.56	0.33	25.92	1.72	0.27	17.86	1.11	0.10	10.89	18.23
284.6	2.58	0.99	31.93	1.89	0.29	19.61	1.25	0.25	13.48	21.67
308.6	2.60	1.00	32.29	2.04	0.32	21.25	1.33	0.36	15.16	22.90
333.7	3.17	1.00	37.39	2.18	0.42	23.30	1.37	0.39	15.80	25.50
380.0	3.39	1.00	39.39	2.43	0.60	27.18	1.43	0.47	17.00	27.86
405.2	3.74	1.01	42.58	2.43	0.61	27.29	1.46	0.50	17.58	29.15

427.8	3.75	1.01	42.74	2.50	0.80	29.65	1.49	0.56	18.40	30.26
452.5	4.69	1.01	51.17	2.60	0.89	31.36	1.52	0.66	19.54	34.02
475.6	5.23	1.01	56.04	2.69	0.94	32.53	1.54	0.72	20.30	36.29

Table A3. g CO₂/kg dry matter of hand shelled in six replicates

Test duration in hours	Replicate						Average of six replicates
	I	II	III	IV	V	VI	
18.7	0.86	0.36	0.91	0.99	0.75	0.41	0.71
42.3	1.69	0.72	1.57	1.80	1.48	0.61	1.31
67.6	2.62	1.04	2.42	2.66	2.29	0.90	1.99
90.0	3.44	1.29	2.54	3.41	3.03	1.15	2.48
115.4	4.21	1.87	2.84	4.19	3.50	1.45	3.01
163.7	6.42	2.81	4.88	4.86	5.05	2.16	4.36
186.4	6.45	3.44	5.78	5.96	5.36	2.16	4.86
210.0	8.31	3.69	6.67	7.20	6.45	2.71	5.84
234.9	9.36	4.12	7.73	8.17	7.54	3.25	6.70
258.6	10.23	4.39	8.74	9.09	7.80	3.69	7.32
281.5	11.13	5.09	8.82	10.07	8.89	4.26	8.04
329.4	13.35	6.04	10.60	11.99	11.19	5.03	9.70

Table A4. g CO₂/kg dry matter of machine shelled corn in six replicates

Test duration in hours	Replicates						Average of six replicates
	I	II	III	IV	V	VI	
18.7	1.46	1.22	1.33	0.60	1.32	0.50	1.07
42.3	3.21	2.70	2.65	1.40	3.40	2.56	2.66
67.6	5.33	4.67	4.49	2.66	5.38	4.29	4.47
90.0	7.53	6.54	6.42	4.22	7.58	6.92	6.54
115.4	9.63	9.36	6.85	5.56	3.80	10.17	7.56
163.7	16.04	14.48	11.65	8.00	13.58	10.88	12.44
186.4	19.46	17.84	13.64	9.75	17.30	12.92	15.15
210.0	23.51	21.71	17.29	11.46	21.34	14.59	18.31
234.9	27.52	25.78	21.09	13.25	25.86	16.46	21.66

Table A5. g CO₂/kg dry matter of undamaged machine shelled corn in six replicates

Test duration in hours	Replicates						Average of six replicates
	I	II	III	IV	V	VI	
18.7	1.02	1.09	0.27	1.05	0.96	1.09	0.73
48.3	1.97	2.16	0.46	2.00	2.06	2.21	1.91
67.6	3.48	3.37	0.66	3.04	3.53	3.60	2.95
90.0	4.47	4.23	0.98	4.43	4.97	4.99	4.01
115.4	5.09	5.26	1.09	6.04	6.21	6.51	5.52
163.7	8.84	8.18	2.71	9.57	10.16	10.39	7.82
186.4	10.63	10.27	3.28	10.20	11.95	12.49	9.80
210.0	13.02	12.56	5.08	13.19	14.22	15.03	12.18
234.9	15.70	13.23	5.37	15.69	16.68	17.61	14.05

Table A6. Comparison of CO₂ production between hand shelled, machine shelled and undamaged machine shelled corn

Test duration in hours	Average of hand shelled corn	Average of undamaged machine shelled corn	Average of machine shelled corn	Ratio of: Un. M.S. ^a H.S.	Ratio of: M.S. ^b H.S. ^c
18.7	0.70	0.73	1.07	1.04	1.53
42.3	1.31	1.91	2.66	1.46	2.03
67.6	1.99	2.95	4.47	1.48	2.25
90.0	2.48	4.01	6.54	1.62	2.64
115.4	3.01	5.52	7.56	1.83	2.51
163.7	4.36	7.82	12.44	1.79	2.85
186.4	4.86	9.80	15.15	2.02	3.12
210.0	5.84	12.18	18.31	2.08	3.13
234.9	6.70	14.05	21.66	2.10	3.23

^aUn. M.S. = undamaged machine shelled.

^bM.S. = machine shelled.

^cH.S. = hand shelled.

Table A7. g CO₂ produced in check (blank) samples and g CO₂/kg dry matter of prepared corn sample

Duration test in hours	Check Samples				0% Damage			
	I	II	III	Average of three replicates	I	II	III	Average of three replicates
18.7	0.07	0.05	0.06	0.06	0.85	0.24	0.63	0.57
42.6	0.08	0.05	0.07	0.07	1.62	0.48	0.98	1.03
68.0	0.08	0.06	0.08	0.07	2.49	0.74	1.85	1.69
90.2	0.09	0.06	0.08	0.08	3.27	0.88	2.65	2.27
115.8	0.09	0.07	0.08	0.08	3.59	1.11	3.02	2.57
164.1	0.11	0.08	0.12	0.10	4.54	1.33	4.94	3.61
186.7	0.29	0.09	0.19	0.19	5.45	1.85	5.98	4.43
210.3	0.36	0.17	0.26	0.26	6.42	2.49	7.01	5.31
235.3	0.36	0.20	0.28	0.28	7.25	2.89	7.67	5.94

Table A8. g CO₂/kg dry matter of shelled corn in prepared samples of 25 and 50% damage

Duration test in hours	25% Damage				50% Damage			
	I	II	III	Average of three replicates	I	II	III	Average of three replicates
18.7	0.72	0.85	1.11	0.89	2.55	0.26	1.58	1.46
42.4	1.34	2.37	1.23	1.65	4.85	0.54	3.68	3.02
67.9	2.88	4.58	1.42	2.96	5.93	1.01	4.31	3.75
90.1	4.82	6.60	1.63	4.35	7.01	1.26	8.70	5.65
115.6	5.44	7.84	1.83	5.04	9.42	1.94	13.34	8.23
163.9	8.46	9.05	2.53	6.68	14.42	4.56	14.08	11.02
186.6	9.61	13.06	3.38	8.68	18.03	5.45	18.25	13.91
210.2	12.86	16.63	3.81	11.10	22.35	6.05	25.19	17.86
235.3	14.27	17.20	4.68	12.05	30.06	8.00	31.60	23.22

Table A9. g CO₂/kg dry matter of shelled corn in prepared samples of 75 and 100% damage

Duration test in hours	75% Damage				100% Damage			
	I	II	III	Average of three replicates	I	II	III	Average of three replicates
19.1	1.50	0.61	0.49	0.87	1.94	2.51	3.02	2.49
42.8	2.65	3.32	0.95	2.31	5.95	3.69	7.54	5.73
68.2	5.04	6.70	1.91	4.55	8.00	8.59	10.11	8.90
90.4	9.22	11.72	2.85	7.93	13.94	8.95	16.71	13.20
115.1	11.40	15.10	5.42	10.63	17.88	13.44	17.39	17.05
164.3	21.04	16.58	6.52	14.72	19.23	19.21	19.83	22.08
187.0	30.22	22.71	9.57	20.83	24.87	30.39	20.90	27.11
210.6	35.53	29.36	11.44	25.20	34.79	36.10	26.08	35.59
235.5	43.50	31.24	14.92	29.57	41.64	43.55	35.88	42.48

Table A10. g CO₂/kg dry matter of machine shelled corn before and after cleaning

Duration of test in hours	Before Cleaning				After Cleaning				Ratio of: <u>Uncleaned</u> <u>Cleaned</u>
	I	II	III	Average of three replicates	I	II	III	Average of three replicates	
23.0	1.76	0.02	2.47	1.42	0.02	1.82	0.31	0.72	1.97
46.4	3.64	0.26	5.47	3.12	0.18	3.08	1.73	1.66	1.88
118.7	6.21	0.39	9.36	5.32	0.37	3.72	2.09	2.06	2.58
143.0	6.23	0.50	14.56	7.10	0.40	4.40	6.02	3.61	1.97

APPENDIX B: DATA ON O₂ CONSUMPTION OF SHELLED
CORN AS RELATED TO RESPIRATION

Table B1. Averaged $\mu\text{L O}_2$ consumption per g dry matter of hand shelled, undamaged machine shelled and machine shelled corn obtained by Gilson Differential Respirometer at different time intervals

Time min.	Hand shelled	Undamaged machine shelled	Machine shelled	Ratio of: $\frac{\text{Undamaged}}{\text{Hand shelled}}$	Ratio of: $\frac{\text{Machine shelled}}{\text{Hand shelled}}$
10	2.2	2.5	2.6	1.1	1.2
20	4.2	5.2	5.4	1.2	1.3
30	6.5	7.8	8.4	1.2	1.3
40	7.8	8.8	10.4	1.1	1.3
50	9.4	11.1	12.6	1.2	1.3
60	10.8	13.2	15.1	1.2	1.4
70	12.7	15.2	17.6	1.2	1.4
80	14.7	17.5	20.1	1.2	1.4
90	16.1	19.2	22.1	1.2	1.4

Table B2. Averaged $\mu\text{L O}_2$ consumption per g dry matter of prepared shelled corn samples with various damage levels at various time intervals

Time, min.	% Damage	25% Damage	50% Damage	75% Damage	100% Damage
10	1.1	2.0	2.5	3.0	3.3
20	2.2	3.3	4.3	6.9	7.1
30	5.6	7.7	9.4	12.6	14.4
40	7.7	10.5	12.8	14.7	19.5
50	10.1	13.2	16.2	22.3	24.2
60	11.3	15.4	19.2	27.5	30.2
70	13.1	17.9	21.9	32.0	35.7
80	14.1	19.6	24.7	37.1	42.0
90	14.3	20.2	26.4	42.5	45.4

APPENDIX C: WATER UPTAKE DATA FOR HAND SHELLED AND
UNDAMAGED MACHINE SHELLED CORN WITH AND
WITHOUT INVISIBLE EXTERNAL CRACKS

Table Cl. g H₂O absorbed by each 100 g shelled corn with initial 25.5% MCWB held in wet towels at 25°C for 52 hours

Duration of test in hours	Undamaged machine shelled corn (possible internal cracks)			Undamaged machine shelled corn (invisible external cracks)		
	Hand shelled corn					
	I	II	III	I	II	III
0	0.07	0.07	0.18	0.06	0.17	0.16
1	1.50	1.51	2.21	3.19	2.45	1.54
2	2.56	2.59	2.62	4.06	3.39	2.53
3	3.15	3.02	3.30	4.63	4.11	3.07
4	3.95	3.64	3.65	5.41	5.10	3.92
5	4.35	3.97	4.30	6.05	5.65	4.28
6	4.85	4.32	4.65	6.55	6.12	4.80
7	5.08	4.70	5.03	6.90	6.58	5.20
8	5.42	4.90	5.25	7.25	6.88	5.32
9	5.82	5.30	5.65	7.75	7.40	6.05
11	6.03	6.04	6.41	8.67	8.35	6.81
13	7.26	6.67	7.09	9.41	8.91	7.59
15	7.95	7.38	7.91	10.21	9.79	8.40
17	8.42	7.94	8.27	10.83	10.65	9.04
19	8.96	8.44	8.84	11.49	11.21	9.36
21	9.34	9.06	9.33	12.21	11.88	10.41
23	10.30	9.84	10.26	12.90	12.68	11.28
25	10.98	10.69	10.95	13.61	13.25	11.98
27	11.71	11.25	11.32	13.98	13.80	12.47
29	12.28	11.98	11.89	14.62	14.32	13.20
31	12.76	12.44	12.06	15.25	15.11	13.90
33	13.40	13.28	13.30	15.58	15.90	14.50
36	14.20	13.99	14.00	16.35	16.65	14.90
39	14.91	14.67	14.86	17.23	17.54	16.04
42	15.52	15.53	15.37	18.06	17.82	16.76
45	16.33	16.89	16.63	19.05	18.98	17.86
48	16.90	17.98	17.70	19.93	19.66	19.19
52	18.45	19.49	18.93	20.53	20.59	20.02